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Environmental Research Laboratories

Some Climatological Characteristics of Seedable Upslope Cloud Systems in the High Plains

C. D. WHITEMAN

BOULDER, COLO.
MARCH 1973

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SOME CLIMATOLOGICAL CHARACTERISTICS OF SEEDABLE UPSLOPE CLOUD SYSTEMS IN THE HIGH PLAINS

C. D. Whiteman

A model of seeding opportunity recognition is developed for shallow wintertime cloud systems in the High Plains of the United States. The model uses rawinsonde network data for the High Plains to determine climatological characteristics of "seedable" upslope cloud systems. Included are annual, monthly, and diurnal frequencies of occurrence of seedable cloud systems as well as characteristics of the cloud systems themselves. Such characteristics include cloud thicknesses, heights of cloud tops and bases, lapse rates, cloud top temperatures, upslope wind components, and the relative frequencies of precipitating and nonprecipitating cloud systems.

1. INTRODUCTION

In the winter season, upslope wind conditions occur frequently in the High Plains region of the United States. These conditions move moisture-laden air up the slope of the High Plains towards the foothills of the Rocky Mountains. The expansion and consequent cooling of the ascending air may result in condensation and generation of widespread decks of stratus or stratocumulus clouds.

Two processes (Fletcher, 1962) may be effective in generating precipitation from these orographic cloud systems:

1. The collision and coalescence of cloud droplets, and
2. The Bergeron-Findeisen process.

The first process may occur in any cloud containing sufficiently large liquid droplets, while the second process requires the presence of ice crystals within a cloud containing supercooled water droplets.

The ice crystals required for the formation of natural precipitation are produced when freezing or sublimation nuclei become effective at existing cloud temperatures, or when ice crystals are introduced directly into the cloud volume from external sources (e.g., natural seeding from nearby clouds containing ice).

Supercooled shallow orographic cloud systems over the High Plains often produce little or no precipitation. These clouds are thought to produce little natural precipitation because of their shallowness, because of the low concentrations of natural ice nuclei active at prevailing cloud temperatures, and because of the inefficiency of the warm rain coalescence process.

On the other hand, the artificial production of significant precipitation from these cloud systems is favored by:

1. A temperature range where their precipitation potential can be released artificially through seeding,
2. The high frequency of these clouds in the High Plains region,
3. The widespread nature of these cloud systems, and
4. Their relatively long duration.

Physical and numerical models have recently been developed for cold orographic cloud systems in the western mountains of the U. S. (e.g., Chappell, 1970; or Willis, 1970). These models, with some modifications, can be adapted to the shallow orographic cloud systems of the High Plains.

Although the seedable cloud systems in the High Plains are similar in some respects to those on the western mountain ranges, some climatological aspects of the High Plains cloud systems are different.

A climatological study of these cloud systems is basic to an investigation of the feasibility of augmenting their natural precipitation. Information required includes synoptic data on the development of upslope storms, as well as their areal coverage, duration, movement, and frequency of occurrence. Characteristics of the clouds, such as cloud thicknesses, lapse rate, cloud top temperatures, and wind speeds and directions, are also related to the natural efficiency of precipitation from these cloud systems.

In this report, a model of the seedability, or potential for artificial release of precipitation from these shallow cloud systems, is developed. Twice-daily rawinsonde data for each station in the High Plains are then compared with the model, and soundings meeting the model criteria are used in the climatology. Results of an investigation into the climatology of seedable orographic cloud systems are presented.

2. A MODEL OF SEEDING OPPORTUNITY RECOGNITION

A model is developed that describes the vertical structure of a theoretically seedable supercooled cloud layer. Figure 1 shows specifications of the model.

Individual rawinsonde soundings are compared with the vertical structure specified in the model. Soundings satisfying the model criteria are considered to indicate the presence of a seedable cloud layer. Model criteria include:

1. A moist layer with relative humidity ≥ 85 percent. This layer defines the vertical extent of the cloud deck.

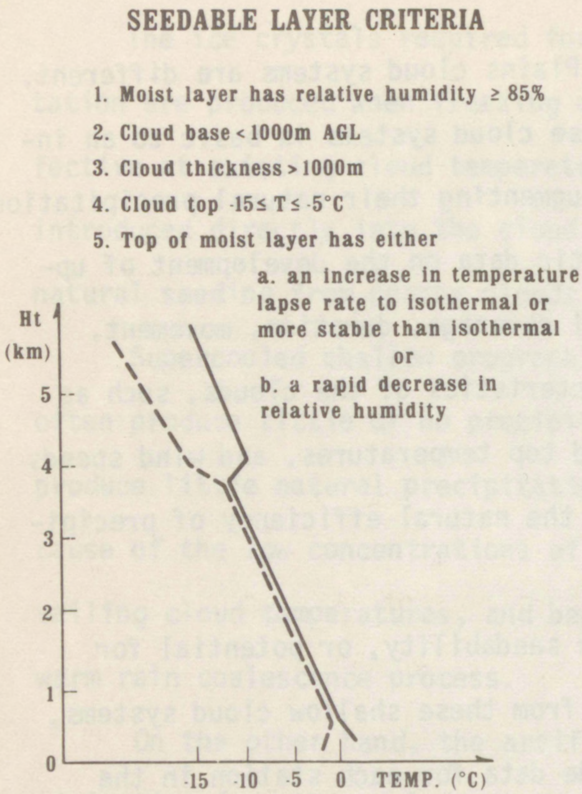


Figure 1: Model criteria for recognition of a seeding opportunity from plotted rawinsonde data.

Super et al. (1971) discussed the determination of cloud base from rawinsonde data and presented the results of 23 rawinsonde observations of typical winter clouds studied during February 1970; they concluded that the mean relative humidity at cloud base was 84.8 percent and the standard deviation was 9.2 percent. The extremes were 100 and 63 percent.

2. A moist layer base within 1 km of the ground. Shallow cloud systems with bases higher than 1 km are assumed to have little potential for artificial precipitation because of the possibility of increased evaporation and sublimation of hydrometers into unsaturated air.

3. A moist layer thicker than 1 km. A layer < 1 km is assumed to be too shallow to produce adequate precipitation at the ground from artificial release. Fletcher (1962) suggested the figure 1300 m as the minimum thickness necessary for a high probability of induced precipitation from silver iodide (AgI) seeding of sub-freezing clouds.

4. A cloud top temperature between -5 and -15°C. Clouds having top temperatures in this range are eminently suitable for artificial release of precipitation, because (1) phase instability of the water substance is often present due to the small number of active natural ice nuclei, and (2) common seeding reagents are available for this temperature range. This author feels that this temperature range is a conservative one, and that experiments on these cloud systems may indicate that the potential for artificial release of precipitation does extend to colder cloud systems. Included in this report is an estimate of the effect a widened range of cloud top temperatures has on the number of occurrences of seedable conditions per year at one of the High Plains rawinsonde stations.

5. A distinct moist layer top. This criterion distinguishes shallow cloud systems from the deep cyclonic storm systems in which the relative humidity appears to decrease slowly with height (fig. 2). A strict interpretation of criterion No. 1 would include some of the deep cyclonic storm systems in the

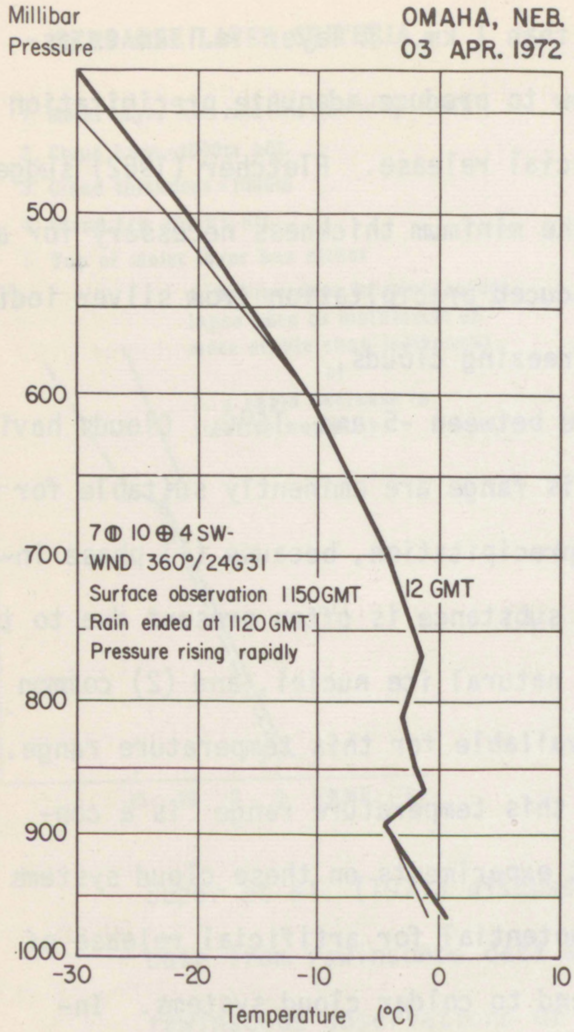


Figure 2: Upper air sounding, in which the dew point temperature drops off slowly with height. The surface observations at the time of release of the rawinsonde are also given.

shallow systems climatology, since deep storm systems often extend to higher levels than indicated by the 85 percent limit. Shallow storm systems generally form below a temperature inversion or are trapped below a layer of dry air. Thus, the top of the moist layer is required to have either a rapid decrease in relative humidity, or an increase in the lapse rate to isothermal or more stable than isothermal. The model requires that the inversion, or dry air layer, be within 50 mb of the top of the moist layer.

The model does not distinguish between the seedability of a cloud layer that is not producing precipitation naturally and one in which precipitation has already begun. Seeding may initiate precipitation, or it may affect the rate of precipitation. Thus, both conditions may be seedable, and the amount of artificial precipitation produced will depend not only on changes in the efficiency of the precipitation process but also on the duration and areal extent of the seeding effect.

Allowance is made to include some "borderline" cases in the climatology when most model specifications are satisfied but others have departures from specifications within the accuracy of the recording equipment. Borderline temperatures are -3 to -5°C and -15 to -17°C, humidities from 80 to 85 percent, moist layer thicknesses from 800 to 1000 m, and temperature inversion, or dry layer, up to 80 mb above the moist layer. A system having moist layers separated by a thin dry layer is also allowed in the analysis when the other criteria are satisfied.

The seedable layer criteria, as defined in figure 1, apply to any existing cloud system in the High Plains, irrespective of the mechanism by which it formed. Shallow upslope storms formed by orographic lifting of moist air will, therefore, not be differentiated from areas of deep fog, or fog that has been lifted to form shallow stratus decks. The addition of a criterion for upslope wind conditions (i.e., an upslope wind component in the sounding somewhere from the surface to 700 mb) will eliminate some fog occurrences from being considered. Note that any fog and stratus decks remaining in the analysis must meet the seedable layer criteria and, therefore, are considered to be available for artificial seeding even though the mechanisms for their formation may be different from those that form the orographic or upslope cloud systems.

3. COLLECTION OF DATA

Fourteen High Plains rawinsonde stations were chosen for the data analysis. For comparison, one additional station (Grand Junction, Colorado) on the western slope of the Rocky Mountains was also included. Each station's records for 10 years of rawinsonde observations were searched for the "cold season," September through April, and all observations that satisfied the seeding model and the upslope wind criteria were pooled for analysis. Data included standard surface observations taken near the time the rawinsonde was released, as well as data taken at the top and base of the moist layer. Figure 3 shows the locations of the rawinsonde stations used in the analysis, figure 4 the topography of the High Plains and its three regions, and table 1 the 10 years of records for each station. We attempted to use the same period for all stations, but availability of data dictated that four stations have slightly different analysis periods than the other 11.

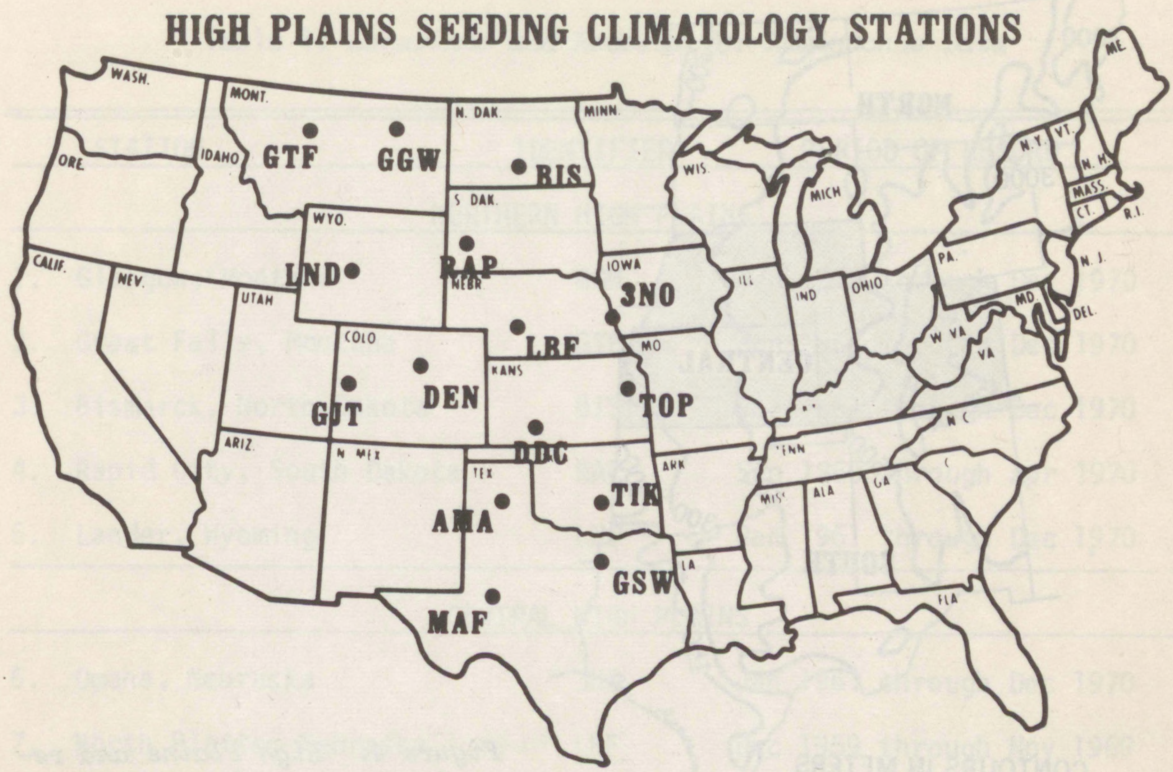


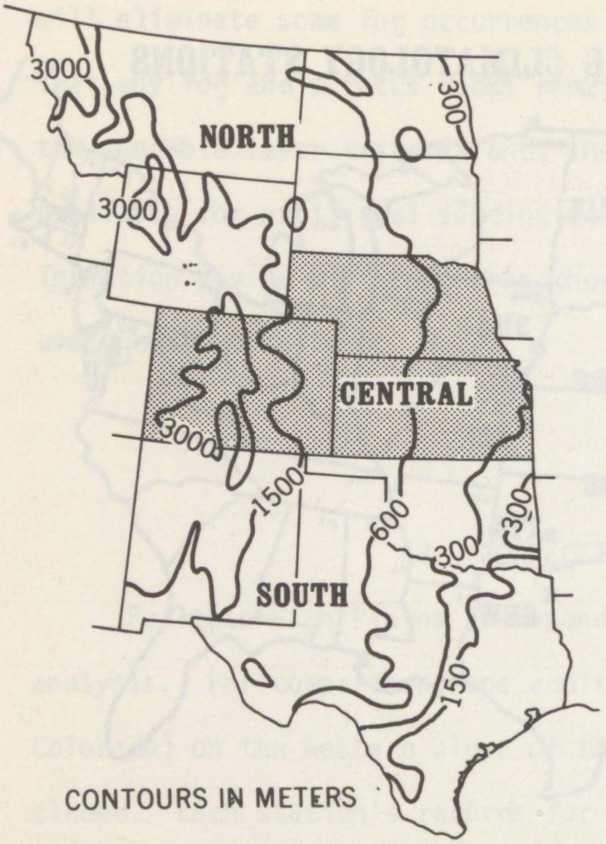
Figure 3: High Plains rawinsonde stations used in the analysis. The names of the National Weather Service Offices correspond to the three-letter identifiers given in table 1.

4. ANALYSIS OF DATA

The following data analysis includes frequencies of occurrence of seedable upslope cloud systems as well as statistics describing the clouds themselves.

4.1. Frequencies of Occurrence of Seedable Cloud Systems

Figure 5 shows the total seedable upslope episodes analyzed at each station. Internal cloud characteristics were determined from as many episodes as possible. The number of occurrences at these individual stations are not directly comparable, however, since some seedable



HIGH PLAINS TOPOGRAPHY

Figure 4: High Plains and regions topography. Contour values are in meters above mean sea level.

upslope conditions were noted on special rawinsonde ascents made at selected stations and times. In figure 6, the number of seedable cloud systems present at standard rawinsonde ascent times (0000 and 1200 GMT) are plotted so that station intercomparisons can be made. The significant points are that:

1. A high frequency of occurrence of seedable upslope systems exists in the northern High Plains.
2. An axis exists from Topeka, Kansas, to Denver, Colorado, along which a secondary maximum is found.

Table 1. *Locations and Records for Rawinsonde Data*

STATION	IDENTIFIER	PERIOD OF RECORD
NORTHERN HIGH PLAINS		
1. Glasgow, Montana	GGW	Jan 1961 through Dec 1970
2. Great Falls, Montana	GTF	Jan 1961 through Dec 1970
3. Bismarck, North Dakota	BIS	Jan 1961 through Dec 1970
4. Rapid City, South Dakota	RAP	Sep 1960 through Apr 1970
5. Lander, Wyoming	LND	Jan 1961 through Dec 1970
CENTRAL HIGH PLAINS		
6. Omaha, Nebraska	3NO	Jan 1961 through Dec 1970
7. North Platte, Nebraska	LBF	Dec 1959 through Nov 1969
8. Denver, Colorado	DEN	Jan 1961 through Dec 1970
9. Topeka, Kansas	TOP	Jan 1961 through Dec 1970
10. Dodge City, Kansas	DDC	Jan 1961 through Dec 1970
SOUTHERN HIGH PLAINS		
11. Oklahoma City, Oklahoma	OKC	Jan 1961 through Dec 1970
12. Amarillo, Texas	AMA	Jan 1961 through Dec 1970
13. Fort Worth, Texas	GSW	Sep 1960 through Apr 1970
14. Midland, Texas	MAF	Oct 1959 through Sep 1969
15. Grand Junction, Colorado	GJT	Jan 1961 through Dec 1970

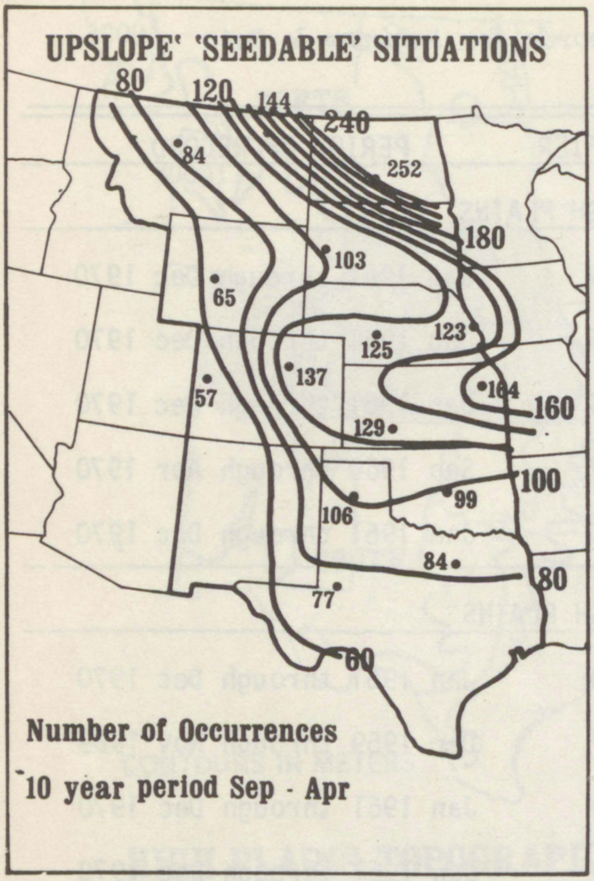


Figure 5: The number of occurrences (September through April) of seedable upslope cloud systems as indicated from all rawinsonde observations in a 10 year period.

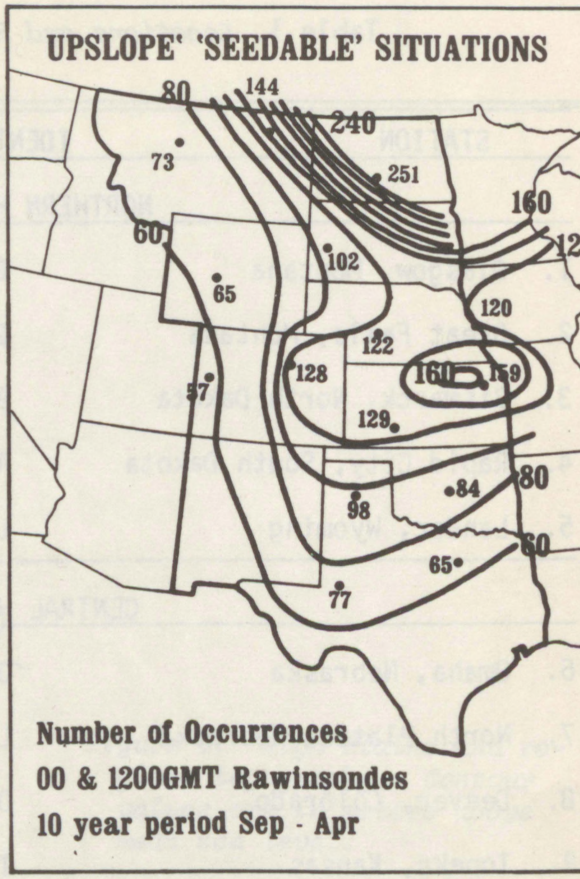


Figure 6: Number of seedable upslope cloud systems (September through April) as indicated on 0000 and 1200 GMT rawinsonde data for a 10 year period.

3. A low frequency of occurrence of seedable upslope systems exists in the southern High Plains.

Figure 7 gives the percentage of morning occurrences (i.e., at 1200 GMT) of seedable upslope conditions compared with the total number of events at 0000 and 1200 GMT. The western High Plains has a higher percentage of morning occurrences than the eastern High Plains stations, although morning occurrences are the most frequent at all stations.

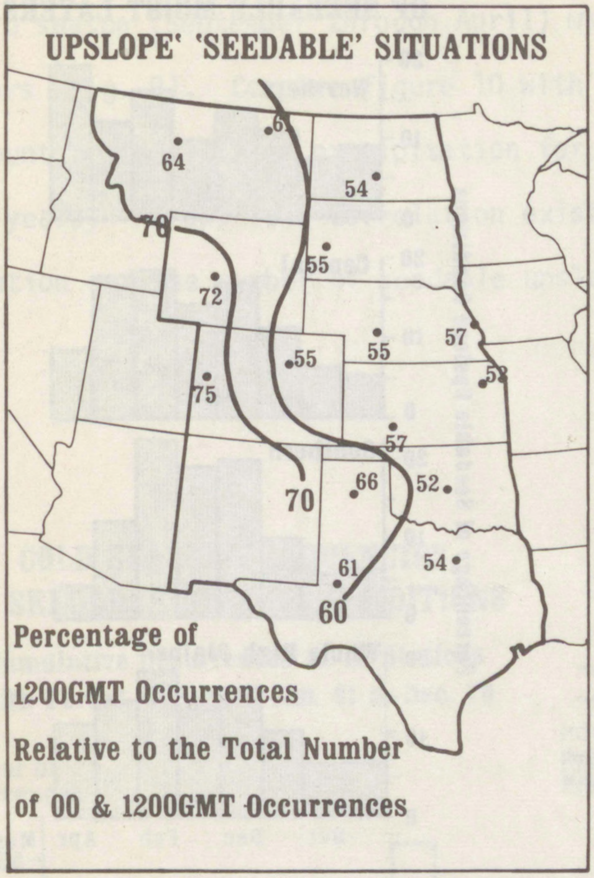


Figure 7: Percentage of morning (1200 GMT) occurrences of seedable upslope cloud systems relative to the total number of morning and evening (0000 GMT) occurrences.

Figure 8 shows the monthly distribution of seedable upslope cloud systems for the three regions of the High Plains, and the average monthly distribution for the entire area. The number of upslope systems in the northern High Plains differs little from month to month, although slightly more do occur in February, March, and April. The graph suggests that additional upslope seedable cloud systems probably arise later in the spring. Midwinter (December through March) is the favored time for these conditions in the central High Plains.

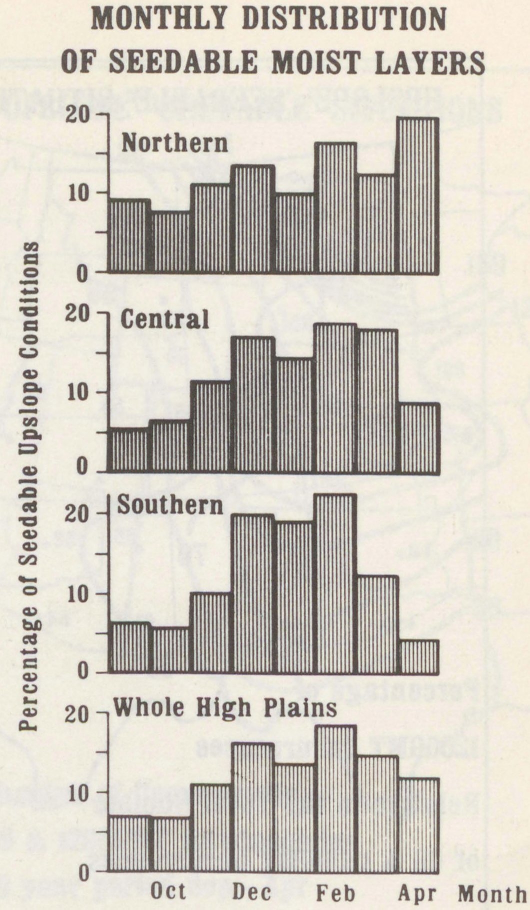


Figure 8: Percentage distribution of seedable upslope conditions during the cold season (September-April) for the High Plains and its regions.

The southern High Plains show an abundance of seedable upslope conditions in December, January, and February; 62 percent of the cold season cloud systems occur in these 3 months.

All regions of the High Plains have relatively few seedable upslope conditions in January as compared with December and February. The flow of moisture into the High Plains is apparently reduced somewhat during January.

4.2 Influence of Upslope Cloud Systems on Cold Season Precipitation

Data were available from 11 rawinsonde stations in the High Plains for the period January 1961 to December 1970. The total number of episodes of seedable upslope conditions at all 11 stations during the cold season (September through April) was plotted for each of the 10 years (fig. 9). Compare figure 10 with figure 9 and note the total amount of cold season precipitation for all 11 stations for the same 10 years. No apparent correlation exists between the actual precipitation and the number of seedable upslope conditions. This suggests

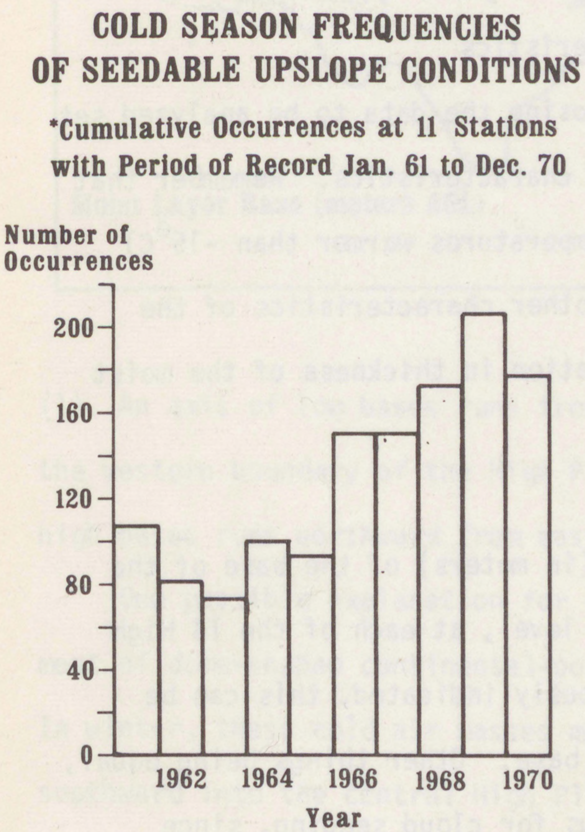


Figure 9: Cumulative number of occurrences of seedable upslope cloud systems for 11 High Plains Stations 1961 through 1970.

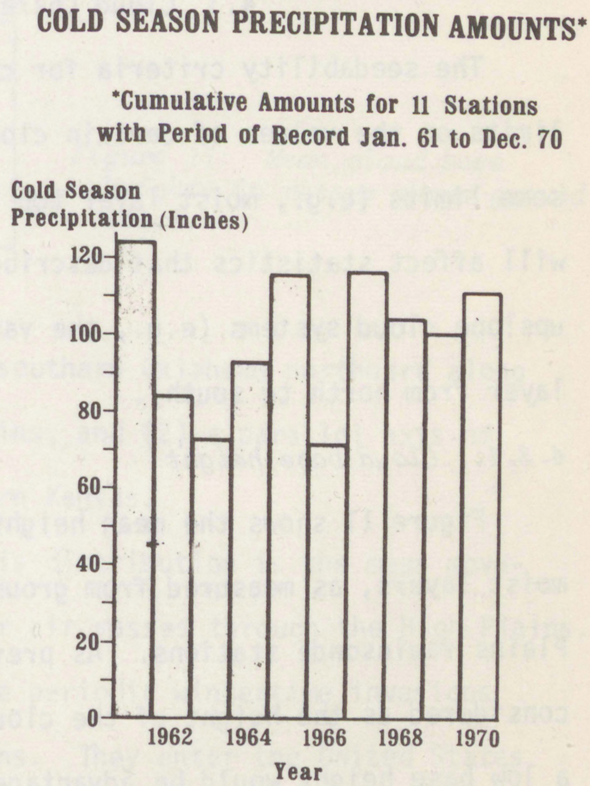


Figure 10: Ten years' cumulative precipitation amounts for the cold season precipitation for 11 High Plains stations 1961 through 1970.

that shallow upslope cloud systems as defined in this study do not contribute the major portion of *natural* precipitation during the cold season. The low correlation may be important, however, during years when the cold season precipitation is low, since seedable upslope cloud systems may be present when the major precipitation-producing systems fail to produce normal amounts. Upslope cloud systems may thus constitute an important potential source of *artificial* precipitation.

4.3 Cloud Characteristics

The seedability criteria for choosing the data to be analyzed set limits on the values of certain cloud characteristics. Remember that some limits (e.g., moist layer top temperatures warmer than $-15^{\circ}C$) will affect statistics that describe other characteristics of the upslope cloud systems (e.g., the variation in thickness of the moist layer from north to south).

4.3.1. Cloud base height

Figure 11 shows the mean height (in meters) of the base of the moist layers, as measured from ground level, at each of the 14 High Plains rawinsonde stations. As previously indicated, this can be considered as the height of the cloud base. Other things being equal, a low base height would be advantageous for cloud seeding, since precipitation would reach the ground with smaller losses from evaporation and sublimation. Although the base heights vary little throughout the High Plains, two distributional characteristics are significant:

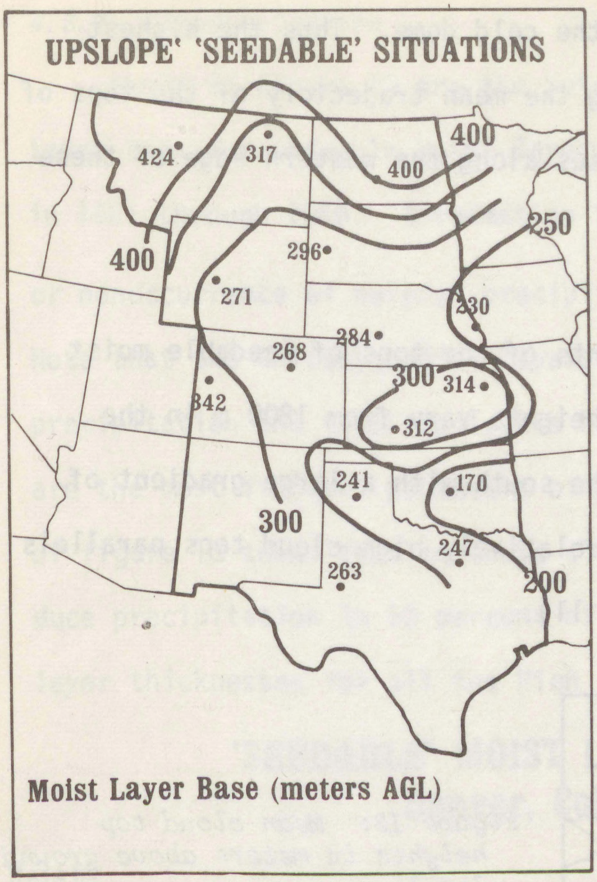


Figure 11: Mean cloud base heights in meters above ground level.

(1) An axis of low bases runs from southern Oklahoma northward along the western boundary of the High Plains, and (2) a parallel axis of high bases runs northward from eastern Kansas.

One possible explanation for this distribution is the mean movement of dome-shaped continental-polar air masses through the High Plains. In winter, these cold air masses make periodic wintertime invasions southward into the central High Plains. They enter the United States from the Great Plains of Canada and generally turn southeastward under the influence of the sloping terrain and the prevailing westerlies. The shallow cold domes are capped by temperature inversions, and the base heights of clouds in these high pressure systems would be expected to parallel the slope of the cold dome. Thus the highest cloud bases might be expected along the mean trajectory of the tops of the cold domes with lower cloud bases along the western edge of these air masses.

4.3.2. Cloud top height

Figure 12 shows the mean heights of the tops of seedable moist layers in the High Plains. These heights vary from 1800 m in the north to approximately 3400 m in the south with a large gradient of heights in the south. An axis of relatively high cloud tops parallels the axis of high cloud bases (fig. 11).

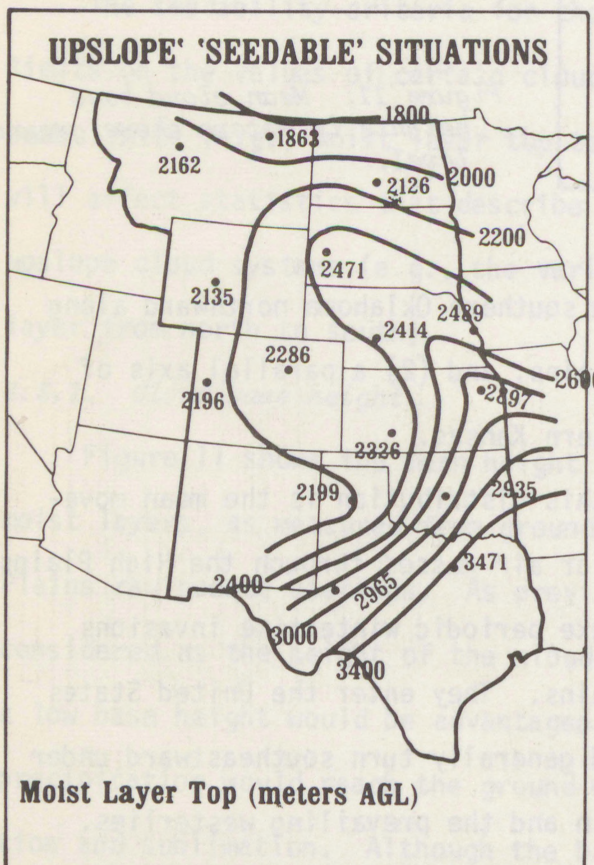


Figure 12: Mean cloud top heights in meters above ground level.

4.3.3 Cloud thickness

Shown in figure 13 are the heights of moist layer bases and moist layer tops for seedable moist layers that occurred at Denver, Colorado, in 1961 through 1966. Information is also presented on the occurrence or nonoccurrence of natural precipitation from these cloud systems. Note that the thickest moist layers frequently are associated with precipitation and that the layers having bases closest to the surface are the most frequent producers of precipitation. Close examination of figure 13 shows that in these cloud systems nature fails to produce precipitation in 50 percent of the potential cases. Mean moist layer thicknesses for all the High Plains rawinsonde stations are

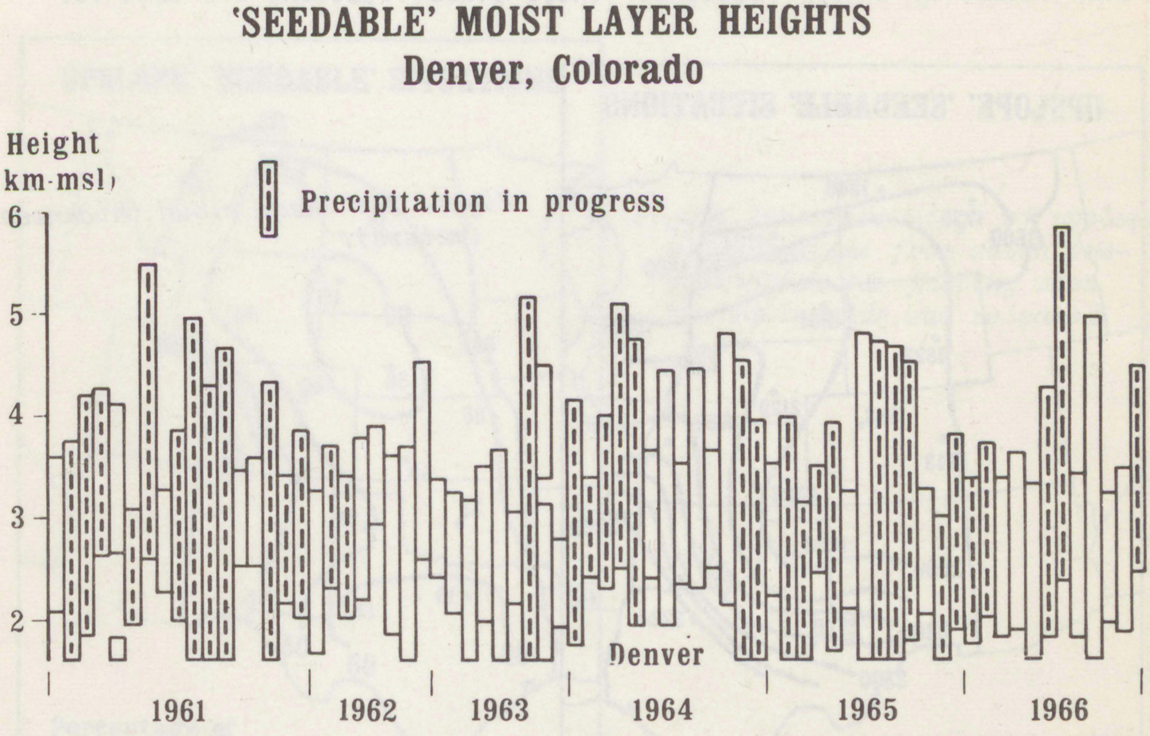


Figure 13: Height of moist layer tops and bases for individual seedable upslope cloud layers at Denver, Colorado, as determined by rawinsonde observations in 1961 through 1966. Dashed lines indicate precipitation in progress at the time of release of the rawinsonde.

shown in figure 14. A steep gradient of thickness exists in the southeastern High Plains; an axis of high thickness values runs from eastern Oklahoma northwestward to central Montana. The temperature criterion in the model causes mean thicknesses to be low in the colder sections of the High Plains and high in the warmer southern sections.

4.3.4. Precipitating layers: frequency of occurrence and intensity of precipitation

Surface observations, taken while the rawinsondes were released, were inspected and any natural precipitation noted. Figure 15 shows the percentage of seedable episodes accompanied by natural precipitation. Table 2 divides the precipitation occurrences into precipitation intensity classifications. These classifications are used for

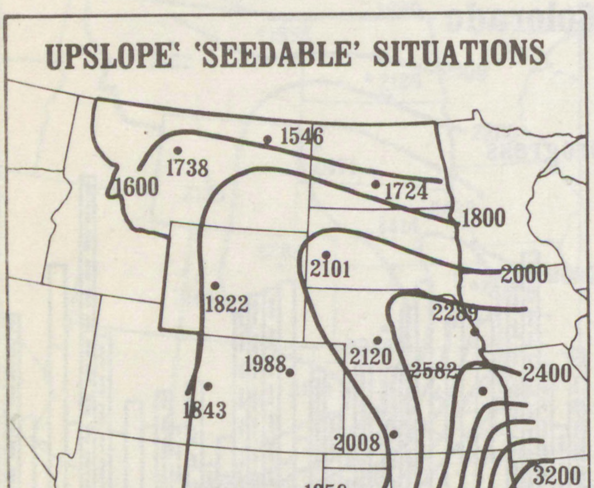


Figure 14: Mean cloud thickness (meters).

surface observations in the United States as defined in the Federal Meteorological Handbook No. 1 (1969) and are presented in Appendix A. The significant information conveyed by table 2 is the high frequency of light and very light precipitation intensities. Although 55 percent of the seedable layers produce precipitation naturally, 95 percent of the natural precipitation is of light or very light intensity. The suitability of these precipitating cloud systems for artificial precipitation augmentation will depend on the new balance that can be attained between artificial changes in the intensity of precipitation and corresponding changes in its duration and areal coverage.

Table 3 shows the relative frequency of morning and evening

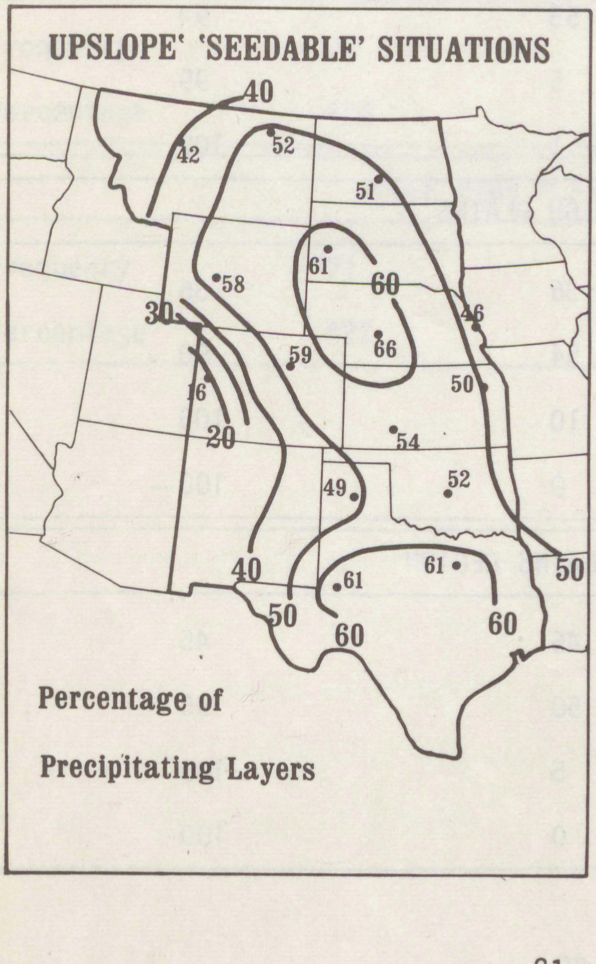


Figure 15: Percentage of upslope cloud systems from which precipitation was falling when the rawinsonde was released.

Table 2. *Precipitation Intensity Frequencies*

PRECIPITATION INTENSITY	FREQUENCY (%)	CUMULATIVE FREQUENCY (%)
NORTHERN HIGH PLAINS		
Very light	54	54
Light	44	98
Moderate	2	100
Heavy	0	100
CENTRAL HIGH PLAINS		
Very light	41	41
Light	53	94
Moderate	5	99
Heavy	1	100
SOUTHERN HIGH PLAINS		
Very light	36	36
Light	54	90
Moderate	10	100
Heavy	0	100
WHOLE HIGH PLAINS REGION		
Very light	45	45
Light	50	95
Moderate	5	100
Heavy	0	100

Table 3. *Precipitation Occurrences*

STATISTIC	NUMBER OF OCCURRENCES 0000 GMT	1200 GMT	TOTALS
NORTHERN HIGH PLAINS			
Frequency	134	201	335
Percentage	40%	60%	100%
CENTRAL HIGH PLAINS			
Frequency	161	196	357
Percentage	45%	55%	100%
SOUTHERN HIGH PLAINS			
Frequency	76	105	181
Percentage	42%	58%	100%
WHOLE HIGH PLAINS REGION			
Frequency	371	502	873
Percentage	42%	58%	100%

precipitation from seedable upslope cloud systems. Morning precipitation is the most frequent, although the preference for morning occurrences is the least pronounced in the central High Plains. In comparison, figure 7 shows that about 55 percent of all precipitation produced in shallow upslope cloud systems also occurs in the morning.

The intensity of precipitation from a seedable upslope cloud system can be plotted against meteorological statistics describing the cloud and its environment. Figures 16 to 19 show the means and standard deviations for each of four variables (cloud thickness, cloud top temperature, lapse rate, and upslope wind component) for each intensity group for each region of the High Plains.

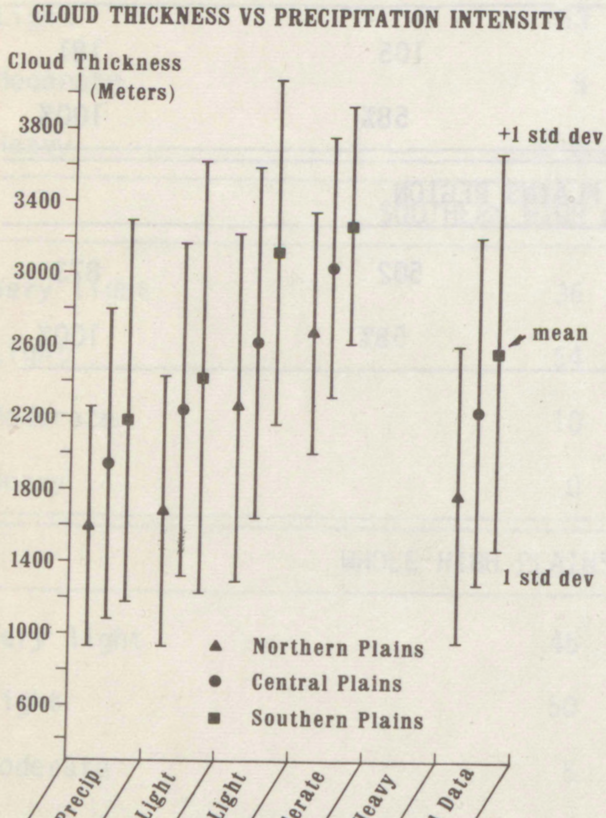


Figure 16: Cloud thickness (meters) versus precipitation intensity for regions of the High Plains. Means and standard deviations of cloud thicknesses are shown. The column "pooled data" gives cloud thickness statistics for each region regardless of precipitation intensity.

The cloud thickness (fig. 16) varies from an average of 1800 m in the northern High Plains to 2600 m in the southern High Plains. The graph clearly shows that the cloud thickness is positively correlated with precipitation intensity within each region. In general, the thicker the cloud, the greater the precipitation intensity. The standard deviations are about 1000 m - a rather high figure - which decreases the utility of the cloud thickness as a single satisfactory predictor of precipitation intensity. The higher categories of precipitation intensity occur infrequently in these shallow cloud systems; consequently, the statistics describing these intensity classifications are based on less data than those describing lighter precipitation intensities.

Similarly, figure 17 shows the effect cloud temperature has on precipitation intensity. Once again the standard deviations are large, although a negative correlation appears between cloud top temperature and precipitation intensity.

The lapse rates of the clouds investigated vary sharply from region to region (see fig. 18); however, no clear-cut differentiation exists between the lapse rates of different precipitation intensity classes within a given region.

The average upslope or east-wind components and their standard deviations (fig. 19) do not change appreciably from region to region. The east-wind values are taken at cloud base and generally average about 2 m sec^{-1} in each of the High Plains regions and have a standard deviation near 4 m sec^{-1}.

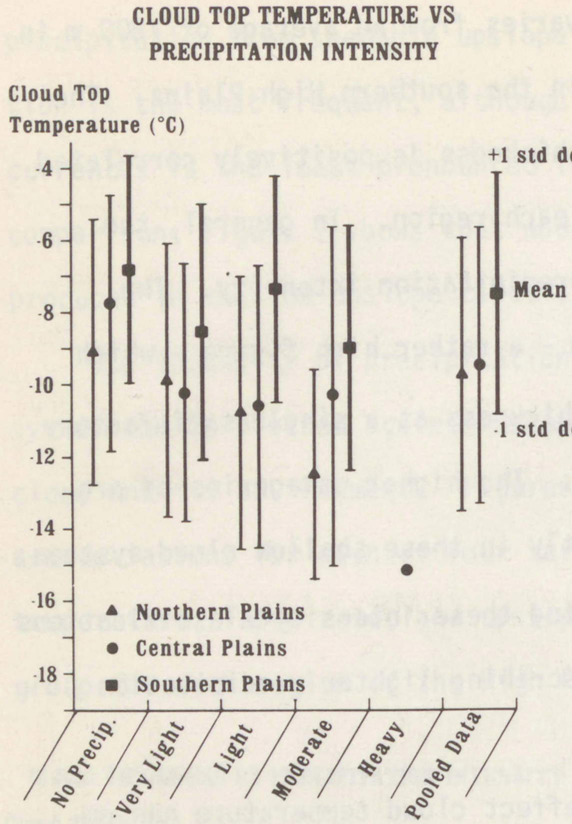


Figure 17: Cloud top temperature (°C) versus precipitation intensity for the High Plains. Means and standard deviations of the lapse rates are shown.

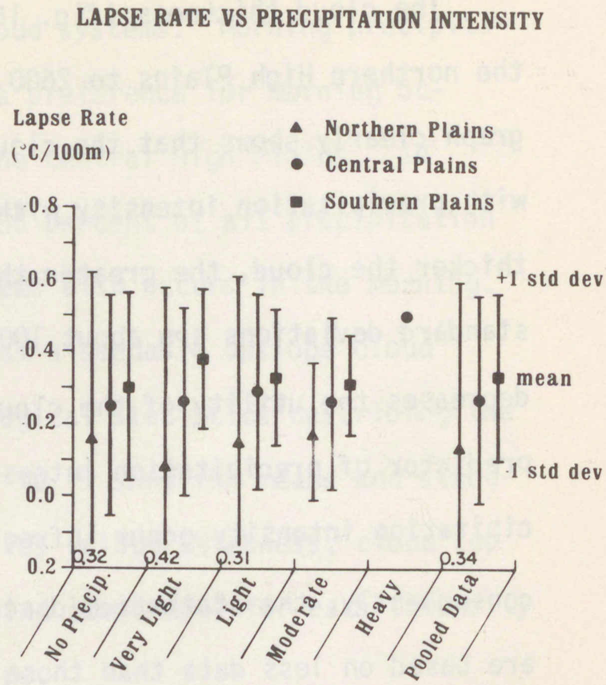


Figure 18: Cloud lapse rate (°C/100 meters) versus precipitation intensity for the High Plains. Means and standard deviations of the lapse rates are shown.

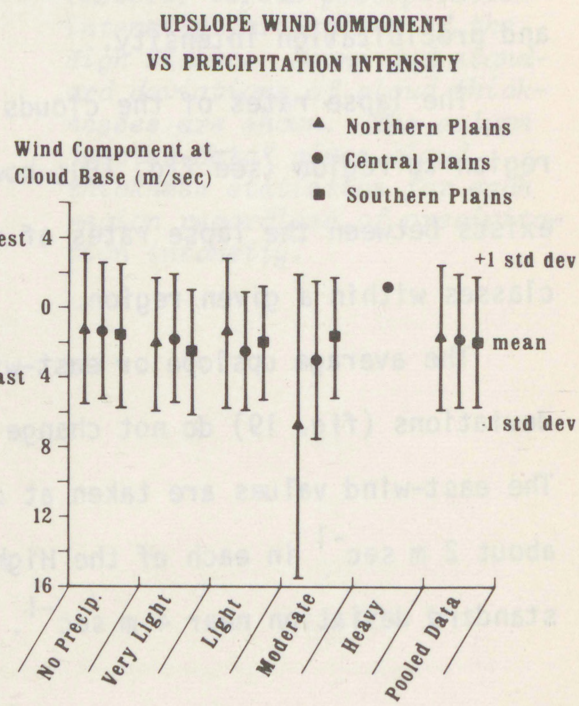


Figure 19: East wind component (meters/second) of cloud base wind speed versus precipitation intensity for the High Plains. Means and standard deviations of the east-wind components are shown.

4.3.5. Temperatures

Figure 20 shows temperatures at the bases and tops of seedable moist layers that occurred at Denver, Colorado, from 1961 to 1966. Also shown are the temperatures at the surface and the occurrence or nonoccurrence of precipitation at the release of the rawinsonde, which provided the data used in the figure. It is apparent that the temperatures are highly variable from storm to storm and that natural precipitation is most frequent when the cloud top temperatures are

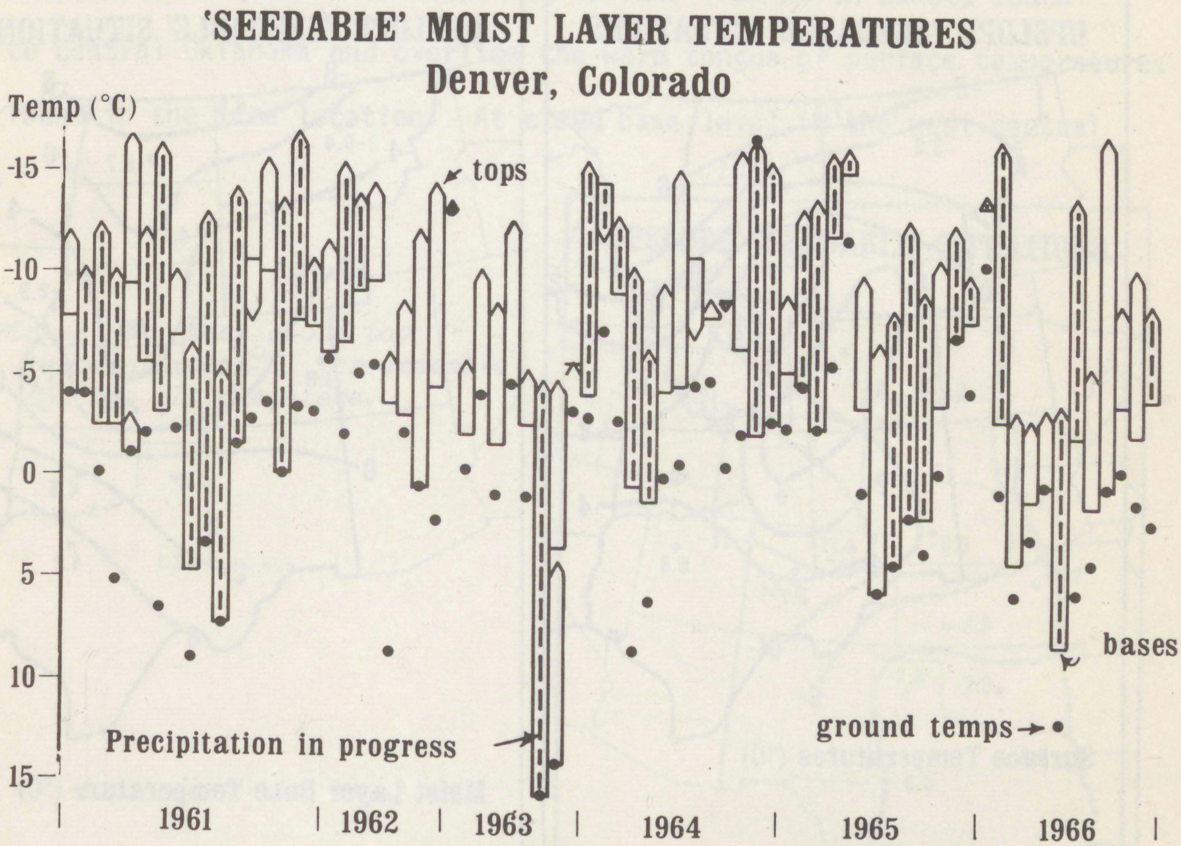


Figure 20: Temperatures at the ground, top of the moist layer, and bottom of the moist layer for individual seedable upslope cloud layers at Denver, Colorado, as determined by rawinsonde observations in 1961 through 1966. Dashed lines indicate precipitation in progress at the time of release of the rawinsonde.

low and the difference between cloud base and cloud top temperatures is greatest.

The distribution of average temperatures for the surface (fig. 21), moist layer base (fig. 22), and moist layer top (fig. 23) for upslope seedable conditions at all rawinsonde stations in the High Plains are shown. Note that the surface temperatures are rather cold, averaging about 4°C in central Texas and -7°C in the northern High Plains. The

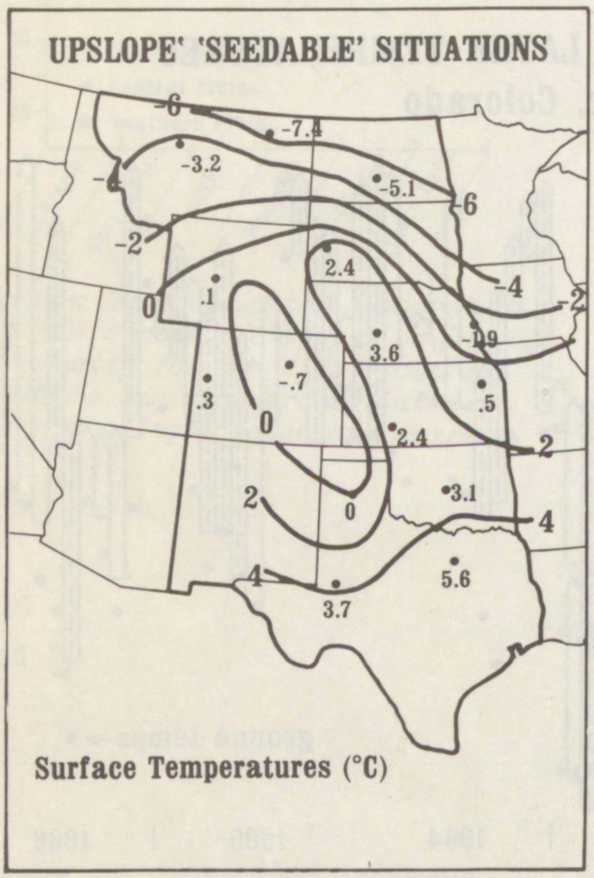


Figure 21: Mean surface temperatures (°C) for seedable upslope episodes.

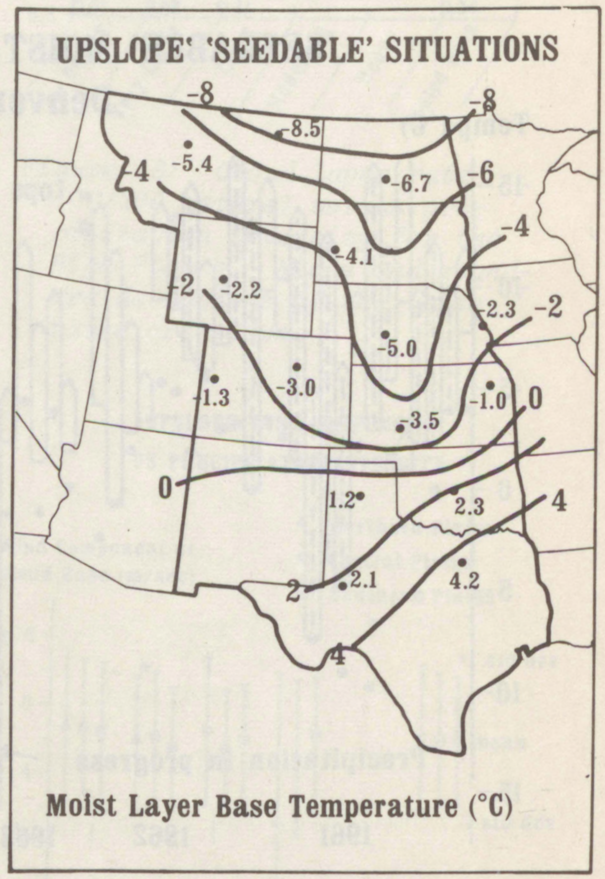


Figure 22: Mean cloud base temperatures (°C) for seedable upslope cloud systems.

remarkable features shown in figure 21 are the pocket of cold air centered over Colorado and the warm air tongue extending north-northwest from eastern Texas.

Cloud base temperatures range from 4°C in the southern High Plains to -9°C in the northern High Plains (fig. 22). Cloud base temperatures in the southern and northern High Plains are about the same as surface temperatures, although in the central High Plains the cloud base temperatures are warmer than surface temperatures. A ridge of cold cloud base temperatures runs from North Dakota south to central Oklahoma and overlies the warm tongue of surface temperatures found in the same location. At cloud base level in the west-central

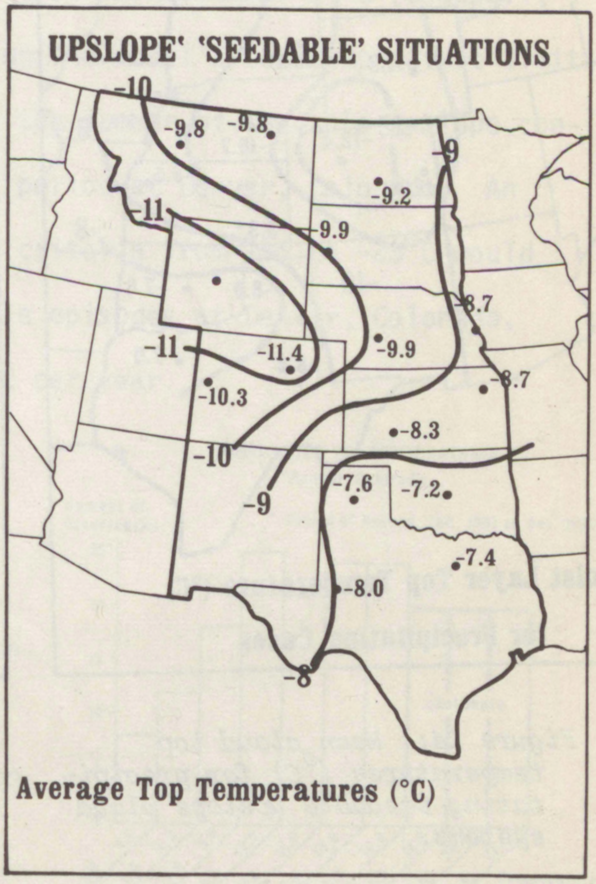


Figure 23: Mean cloud top temperatures (°C) for seedable upslope cloud systems.

High Plains, there is little indication of the isolated cold air pocket appearing on the surface.

The moist layer top temperatures (fig. 23) are lowest in the western, higher elevation portions of the High Plains; Denver, Colorado, and Lander, Wyoming, have the lowest top temperatures.

It is instructive to compare the average cloud top temperatures of precipitating layers (fig. 24) with those of nonprecipitating layers (fig. 25). For the nonprecipitating cases, the top tempera-

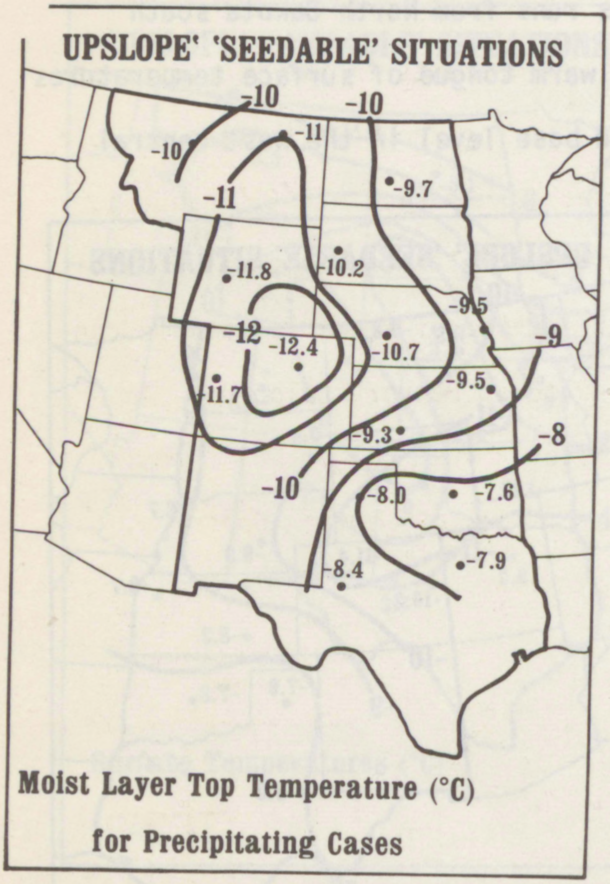


Figure 24: Mean cloud top temperatures (°C) for precipitating seedable upslope cloud systems.

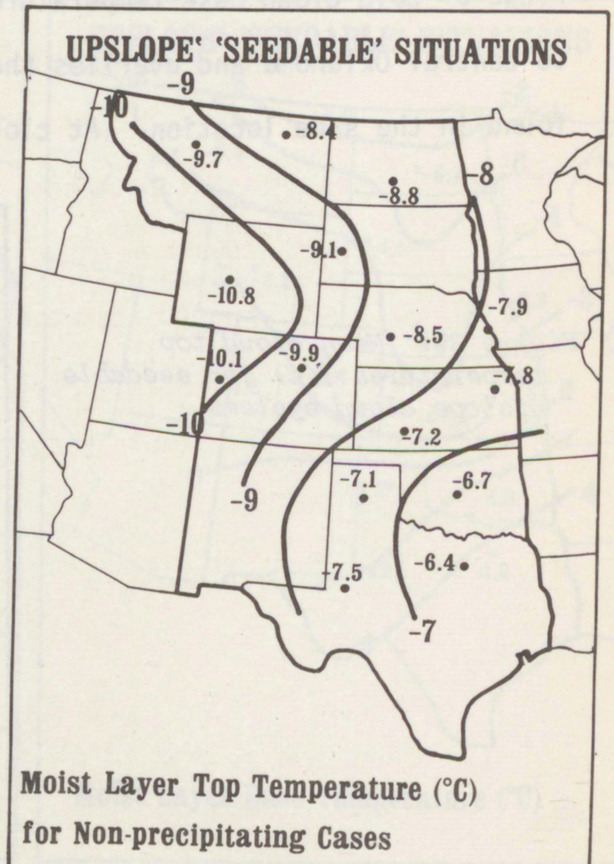


Figure 25: Mean cloud top temperatures (°C) for nonprecipitating seedable upslope cloud systems.

tures vary from a high of -6°C in the southeast to a low of -11°C in the west-central High Plains. The mean top temperatures for precipitating systems are 1.4°C colder than those of nonprecipitating systems and have an axis of cold top temperatures oriented north-south lying along the western edge of the High Plains. This relationship between cloud top temperature and precipitation is logical because cold temperatures would lead to larger numbers of active freezing nuclei and would generally indicate thicker cloud layers. Both conditions would be favorable for producing precipitation.

Results of several cloud seeding experiments in the mountains of the Western U. S. have indicated that seeding can be effective on cold orographic clouds with top temperatures warmer than -24°C (Chappell, 1972). Figure 26 shows how changing the model's top temperature limit from -15°C to -23°C would increase the number of seedable upslope conditions by 45 percent in a 10 year period at Denver, Colorado. An extension of the temperature range criteria from -15 to -23°C would thus increase the number of seedable episodes at Denver, Colorado, from 13.7 per year (fig. 5) to 19.2 per year.

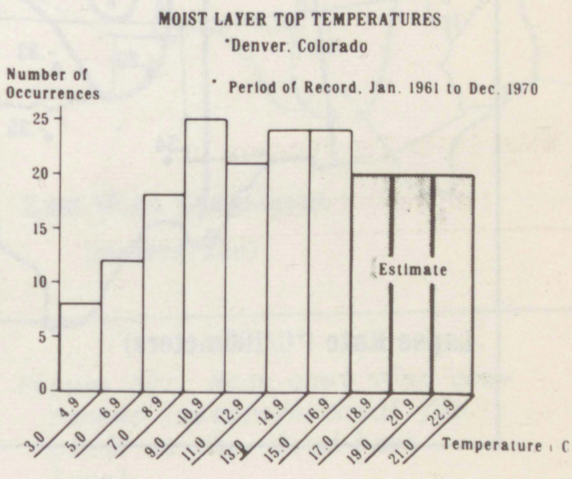


Figure 26: Cold season frequency distribution of cloud top temperatures for seedable upslope cloud systems at Denver, Colorado, for the 10 years from January 1961 to December 1970. An estimate of the frequency distribution for cloud top temperatures below -17°C is indicated on the figure.

4.3.6. Lapse rates

Temperature lapse rates were calculated for all moist layers by dividing the temperature difference between the tops and bases of the layers by the thicknesses of the moist layers. Figure 27 shows the variation of average lapse rate across the High Plains, with generally stable lapse rates in the northern High Plains, and less stable temperature structures along the mountains and in the south. Note that lapse rates throughout the High Plains are, on the average, more stable than moist adiabatic (approx. 0.6^{o}C per 100 m) and less stable than isothermal. The percentage of moist layer inversions (fig. 28) in the complete record of seedable upslope episodes follows the same general

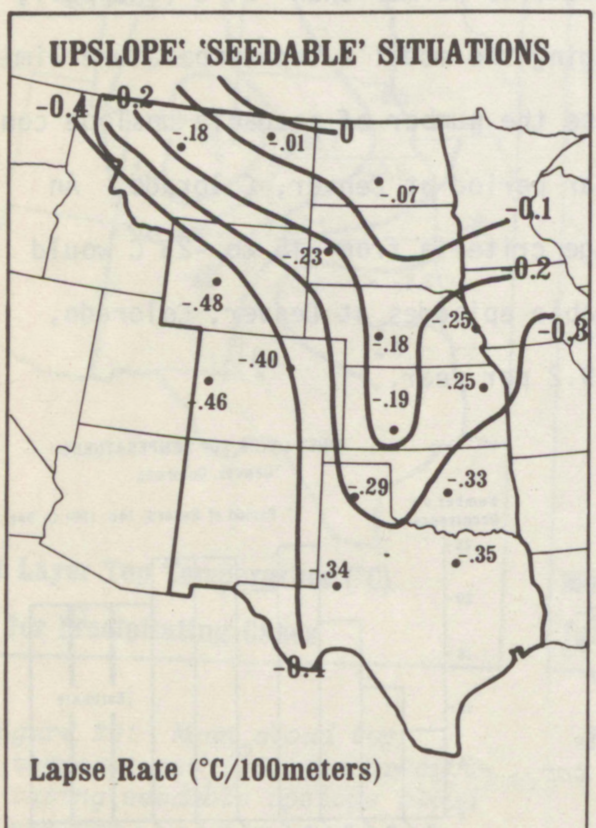


Figure 27: Mean lapse rates (^{o}C/100 meters) for seedable upslope cloud systems.

pattern as the lapse rates. Note that the northern High Plains have stable cloud systems and frequent inversions.

4.3.7. Wind speeds and upslope wind components

The average east-wind component of the cloud base wind speeds were calculated for each rawinsonde station (fig. 29). Most upslope, or east wind, components were only 1 or 2 m sec^{-1} with the axis of maximum values running NNE-SSW through western Kansas.

Tabulated wind speed data were also averaged over all directions for each station and plotted for three levels - the surface (fig. 30),

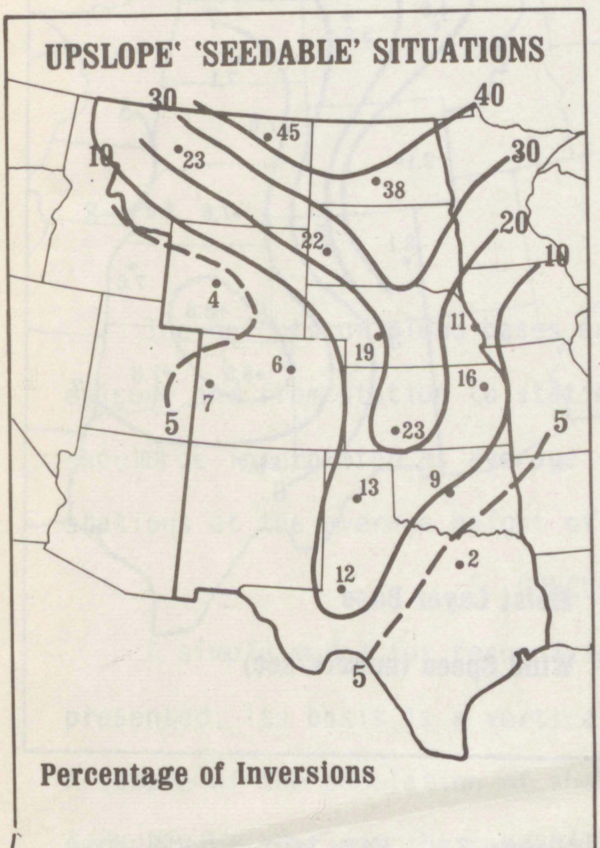


Figure 28: Relative frequency (%) of moist layer temperature inversions.

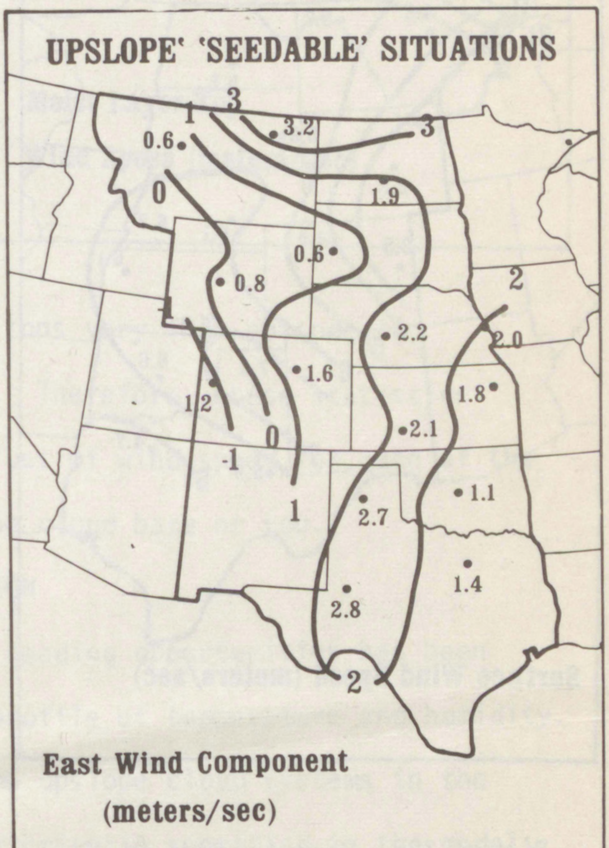


Figure 29: Mean east wind component (meters/second) for winds at the cloud base level.

the base of the cloud deck or moist layer (fig. 31), and the top of the moist layer (fig. 32). The surface wind speeds and the cloud base wind speeds follow the same pattern with the highest speeds on an axis from northern Texas to eastern Nebraska. Cloud top wind speeds (fig. 32) are about 11 m sec^{-1} across most of the High Plains with a maximum at Fort Worth, Texas, of 13.9 m sec^{-1}.

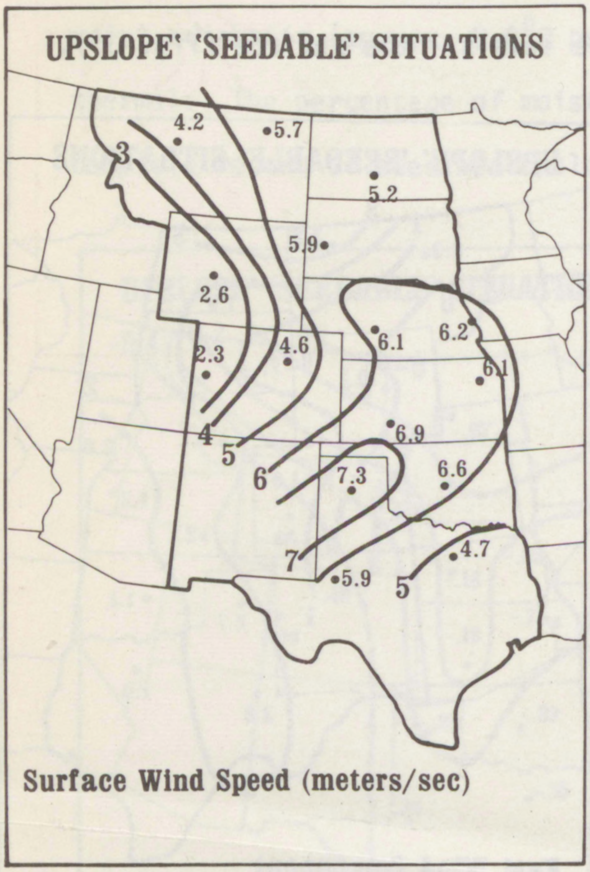


Figure 30: Mean surface wind speed (meters/second) averaged over all directions for seedable upslope episodes.

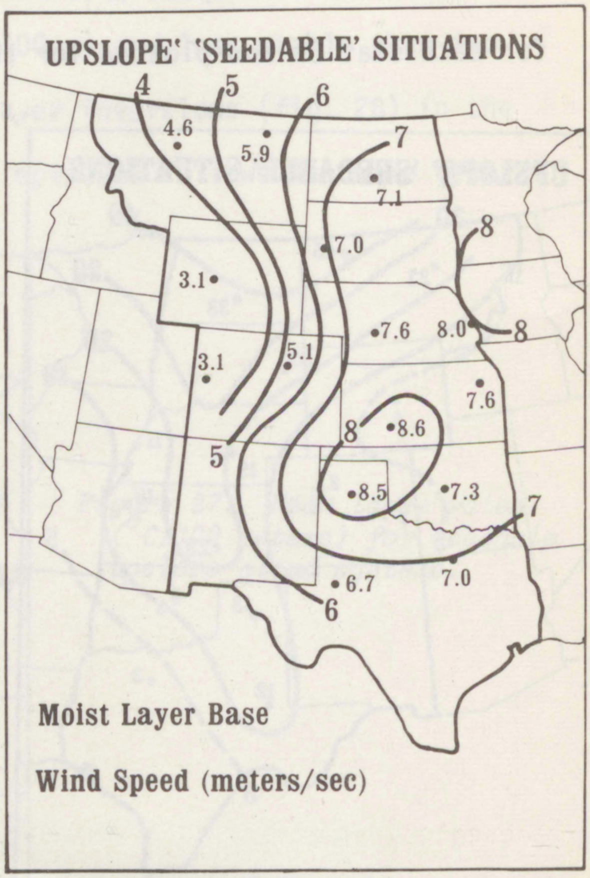
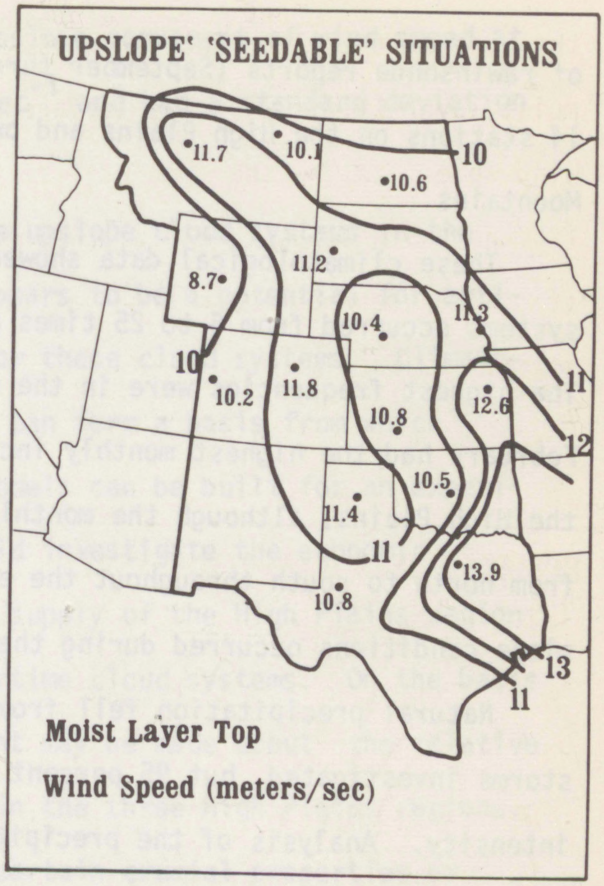


Figure 31: Mean cloud base wind speed (meters/second) averaged over all directions for seedable upslope episodes.

Figure 32: Mean cloud top wind speeds (meters/second) averaged overall directions for seedable upslope episodes.



The heights of cloud bases and tops vary from episode to episode and from station to station. Therefore, these statistics should be interpreted as average values of wind speed for each of the stations at the average height of the cloud base or top.

5. CONCLUSION

A simple model for recognizing seeding opportunities has been presented; its basis is a vertical profile of temperature and humidity. A sample of the population of shallow upslope cloud systems in the High Plains that met the seedability criteria specified in the model was statistically analyzed. Characteristics of these cloud systems and their distribution in space and time were determined from 10 years of rawinsonde reports (September through April) for 15 stations – 14 stations on the High Plains and one station west of the Rocky Mountains.

These climatological data showed that seedable upslope cloud systems occurred from 6 to 25 times per year at individual stations. The highest frequencies were in the northern and central High Plains. February had the highest monthly incidence of upslope conditions in the High Plains, although the monthly distribution varied considerably from north to south throughout the entire region. Most seedable upslope conditions occurred during the morning (the 1200 GMT sounding).

Natural precipitation fell from 55 percent of the shallow upslope storms investigated, but 95 percent of this was of light or very light intensity. Analysis of the precipitation intensities of these cloud systems has shown a direct relationship between precipitation intensity and cloud thickness within three regions of the High Plains. Similarly, cloud top temperature appears to be inversely related to precipitation intensity in the northern and central High Plains, although the relationship is less clear in the southern Plains.

The average seedable cloud layer had a base 300 m above ground and a thickness of approximately 2600 m. The lapse rates of these cloud systems differed markedly across the High Plains, with stable lapse rates in the north (generally +0.00 °C per 100 m to -0.25°C per 100 m) and less stable lapse rates in the west and south (-0.25°C per

100 m to -0.50°C per 100 m). The upslope component of wind speed at cloud base was generally 1 to 2 m sec^{-1} and had a standard deviation of 3 or 4 m sec^{-1}

The high incidence of seedable upslope cloud systems in the High Plains indicates that there appears to be a potential for artificial precipitation augmentation for these cloud systems. Climatological data on these cloud systems can form a basis from which required physical and statistical models can be built for an experimental program. Such a program could investigate the economic feasibility of augmenting the water supply of the High Plains region by artificially seeding these wintertime cloud systems. On the basis of this analysis, a guarded statement may be made about the relative artificial precipitation potential in the three High Plains regions. Some of the analyses have unveiled certain crucial properties or characteristics of upslope cloud systems that may affect their precipitation potential in some parts of the High Plains. For instance, figure 28 indicates that cloud systems in the northern High Plains, even though most frequent in occurrence (fig. 6), have the highest percentage of moist layer inversions. Their overall stability may be a strong influence against the efficient production of artificial precipitation from these cloud systems. Figures 16 to 18, on the other hand, seem to support the argument that upslope cloud systems in the southern High Plains may prove to be the most promising for the enhancement of winter precipitation. Southern Plains systems have the warmest cloud top temperatures, the steepest lapse rates, the greatest depth, and thus appear to be of a more convective nature than cloud systems farther north. This statement must, of course, be weighed against the important data, presented in figures 5 and 6, on the frequency of occurrence of upslope cloud systems. The potential for artificial release of precipitation from shallow upslope cloud systems must, of course, be weighed against the need for cold season precipitation in the area chosen, the crop cycle, the presence of unusual precipitation cycles, and other economic considerations.

Further climatological studies are necessary to adequately understand the natural characteristics of these storms. Their areal coverage, duration, and movement across the High Plains; their distribution of natural precipitation; and their natural efficiency in converting water vapor to precipitation must all be known. Estimates of the change in efficiency produced by seeding will enable us to appraise the magnitude of the increases in precipitation to be expected from artificial seeding.

Synoptic climatological investigations and the development of numerical and statistical models of seedable upslope cloud systems should be pursued. They could provide vital forecast capability and form an objective basis for operational decisions.

6. ACKNOWLEDGEMENTS

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APPENDIX A

Intensity of Precipitation

The intensity of precipitation indicates the amount of precipitation falling at the time of an observation (Federal Meteorological Handbook, 1969). Intensity is expressed as very light, light, moderate, or heavy. The meaning of each intensity depends on the type of precipitation and the method used to determine the intensity. The different intensities are contained in tables A-1 through A-5 taken from the Federal Meteorological Handbook (1969).

A. Intensity of Freezing Precipitation.

1. *Freezing Drizzle.* When freezing drizzle is occurring alone, the intensity is determined by use of table A-3, Visibility as Criteria. Table A-2, Rate-of-Fall as Criteria is used if drizzle is occurring with other phenomena.

2. *Freezing Rain.* The intensity of freezing rain is determined using table A-1, Rate-of-Fall Criteria for Precipitation, if a recording or totalizing gage is available, otherwise table A-5, Estimating Intensity of Rain, is used.

B. Intensity of Ice Pellets

The intensity of ice pellets is determined by using table A-1, Rate-of-Fall Criteria, if recording or totalizing gages are available, otherwise the intensity is estimated in accordance with table A-4, Estimating Intensity of Ice Pellets.

C. Intensity of other Precipitation

1. *Rain.* The intensity of rain is determined on the basis of rate of fall, table A-1, if a recording gage or totalizing gage is available. If other precipitation is also occurring, that portion of the rate of fall associated with the rain is estimated. If a recording of totalized gage is not available, the intensity is estimated in accordance with table A-5.

2. *Drizzle with Other Precipitation.* Intensity is determined on the basis of rate of fall using table A-2.

3. *Snow, Drizzle, Snow Grains, or Snow Pellets Occurring Alone.* Intensity is determined in accordance with table A-3.

4. *Snow, Snow Grains, or Snow Pellets Occurring with Other Precipitation or Obstructions to Vision.* Intensity is estimated on the basis of experience with the apparent rate of fall. The intensity determined must not be higher than that which would be determined using the reported visibility as the criteria.

Table A-1. *Intensity of Precipitation (other than drizzle) on Rate-of-Fall Basis*

Very light	Scattered drops or flakes that do not completely wet or cover an exposed surface, regardless of duration.
Light	Trace to 0.10 inch per hour; maximum 0.01 inch in 6 min.
Moderate	0.11 inch to 0.30 inch per hour; more than 0.01 inch to 0.03 inch in 6 min.
Heavy	More than 0.30 inch per hour; more than 0.03 inch in 6 min.

Table A-2. *Intensity of Drizzle on Rate-of-Fall Basis*

Very light	Scattered drops that do not completely wet an exposed surface, regardless of duration.
Light	Trace to 0.01 inch per hour.
Moderate	More than 0.01 inch to 0.02 inch per hour.
Heavy	More than 0.02 inch per hour

Table A-3. *Intensity of Drizzle and Snow with Visibility as Criteria*

Very light	Scattered flakes or droplets that do not completely cover or wet an exposed surface, regardless of duration.
Light	Visibility 5/8 statute mile or more.
Moderate	Visibility less than 5/8 statute mile but less than 5/16 statute mile.
Heavy	Visibility less than 5/16 statute mile.

Table A-4. *Estimating the Intensity of Ice Pellets*

Very light	Scattered pellets with no accumulation.
Light	Few pellets falling with no appreciable accumulation.
Moderate	Slow accumulation.
Heavy	Rapid accumulation

Table A-5. *Estimating the Intensity of Rain*

Very light	Scattered drops that do not completely wet an exposed surface, regardless of duration.
Light	Individual drops are easily seen; slight spray is observed over pavements; puddles form slowly; over 2 min. may be required to wet pavements completely; sound on roofs ranges from slow pattering to gentle swishing; steady small streams may flow in gutters and downspouts.
Moderate	Individual drops and not clearly identifiable; spray is observable just above pavements and other hard surfaces, puddles form rapidly; downspouts on buildings seen 1/4 to 1/2 full; sound on roofs ranges from swishing to gentle roar.
Heavy	Rain seemingly falls in sheets; individual drops are not identifiable; heavy spray to height of several inches is observed over hard surfaces; downspouts run more than 1/2 full; visibility is greatly reduced; sound on roofs resembles roll of drums or distant roar.

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