EG&G

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31 AUGUST 1971

VOLUME I

COLORADO RIVER BASIN PILOT PROJECT

COMPREHENSIVE ATMOSPHERIC DATA REPORT

PHASE II WINTER SEASON 1970-71

0248

ALBUQUERQUE DIVISION, SERVICES AND SYSTEMS GROUP
EG&G INC., 933 BRADBURY DR. S.E. ALBUQUERQUE, N. M. 87106

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PHASE II WINTER SEASON 1970-71

Prepared for

U.S. Department of the Interior
Bureau of Reclamation
Office of Atmospheric Water Resources

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CHAPTER 1
INTRODUCTION

The purpose of the Colorado River Basin Pilot Project is to produce positive increases in snowfall over large areas of the San Juan Mountains and to provide for sound scientific, engineering, and economic evaluations of the precipitation increases as well as of the technology used. The experimental results of the Climax Program (Climax, Colorado), and the cloud modification models thereby developed, are the basis for this pilot project.

This Comprehensive Atmospheric Data Report provides an annual compilation of meteorological data that can be used to support seeding activities. The data compilation is intended for use by others in evaluating and analyzing precipitation increases and other effects of the cloud seeding conducted during the course of the project. (The actual seeding data are contained in a companion Comprehensive Seeding Report.) This Comprehensive Atmospheric Data Report is largely a data compilation, but some summary and analysis material is presented.

The report, in broadest terms, consists of two segments:

1) Five chapters which provide a general discussion of the project, operational methods, and local meteorology.

2) A sixth chapter which provides data summaries for each experimental day, including an extensive compilation of pertinent maps, graphs, photographs, and tables.

CHAPTER 2
PROJECT DESCRIPTION

2.1 GOAL

The project goal is to give the Bureau of Reclamation a supportable basis for recommending by the mid-1970's an early operational program to augment the Colorado River water supply. Plans for an operational seeding program – including estimates of possible water augmentation at identified probability levels; program operational and other associated costs; and necessary legal, social, and environmental arrangements – will primarily be developed from the pilot project evaluations and data.

Pilot project summary reports and recommended operational plans will be included in the comprehensive investigations required under Title II of the Colorado River Basin Project Act.

2.2 PHYSICAL BASIS AND SCIENTIFIC REASONS FOR THE PROJECT

Experiments by Colorado State University near Climax, Colorado, and at Wolf Creek Pass, Colorado, showed with statistical significance that winter precipitation was substantially increased during certain identifiable storm situations using ground-based silver iodide generators. The experimental field testing by E. Bollay Associates at Steamboat Springs, Colorado, identified and resolved many of the engineering system and seeding delivery problems typical of the region. These experiments, combined with results of other research and commercial operations, confirmed the possibility that a substantial economic augmentation of the Colorado River could begin within the next decade through cloud seeding.

The main new evidence from these recent research activities is that only 20 to 40 percent of the storms are favorable for increasing precipitation by seeding and that these storm situations can now be identified with reasonable confidence. Increases effected by seeding during favorable situations are on the order of 50 to 100 percent. Those situations where seeding causes no effect or where precipitation decreases occur can also be identified.

However, there are many questions concerning how realistically and reliably experimental and research results can be extrapolated to plans and estimates for a full-scale operational program. Uncertainties include extrapolating the validity of experimental increases to large areas, comparability of any peculiar smaller experimental target area effects to those anticipated over more complex and larger areas, comparability of the efficiency and effectiveness of experimental-type seeding to operational-type seeding, and determination of any downwind effects from a major seeding activity. Uncertainties over social and environmental considerations do not become fully apparent during experiments. Before the Bureau of Reclamation could responsibly recommend and justifiably support an operational program, with reasonable chance of its being fully considered, a firm basis for answering these questions must be established. It is the goal of the Colorado River Basin Pilot Project to provide this firm basis.

2.3 PROJECT AREA

The Colorado River Basin Pilot Project includes a 3,300 square mile area in the San Juan Mountains of southwestern Colorado (Figure 2-1) where elevations generally exceed 9,500 feet. This is the area where deep snowpacks accumulate averaging up to 7 feet, equivalent to 30 inches of water. During the winter season, mid-October through mid-May, precipitation averages 24 inches over the area with over 40 inches received on the high ridges and peaks. Seeding experiments at Climax, Colorado, and at Wolf Creek Pass indicate snowfall in this area could be increased 30 to 35 percent by seeding.

The project area is divided into four subareas according to the wind directions most significant in producing snowfall in each area. These are numbered in their respective priority for best seeding with Subarea 1 having the most favorable seeding opportunities with more warm, southwest flow situations, best conditions and access for evaluation, and least expected social and environmental problems. Subarea 4 has the least number of favorable seeding opportunities with more cold northwest flow storms, more rugged access for evaluation, more complex terrain, and more social and environmental problems, including the severe avalanche area on Red Mountain Pass.

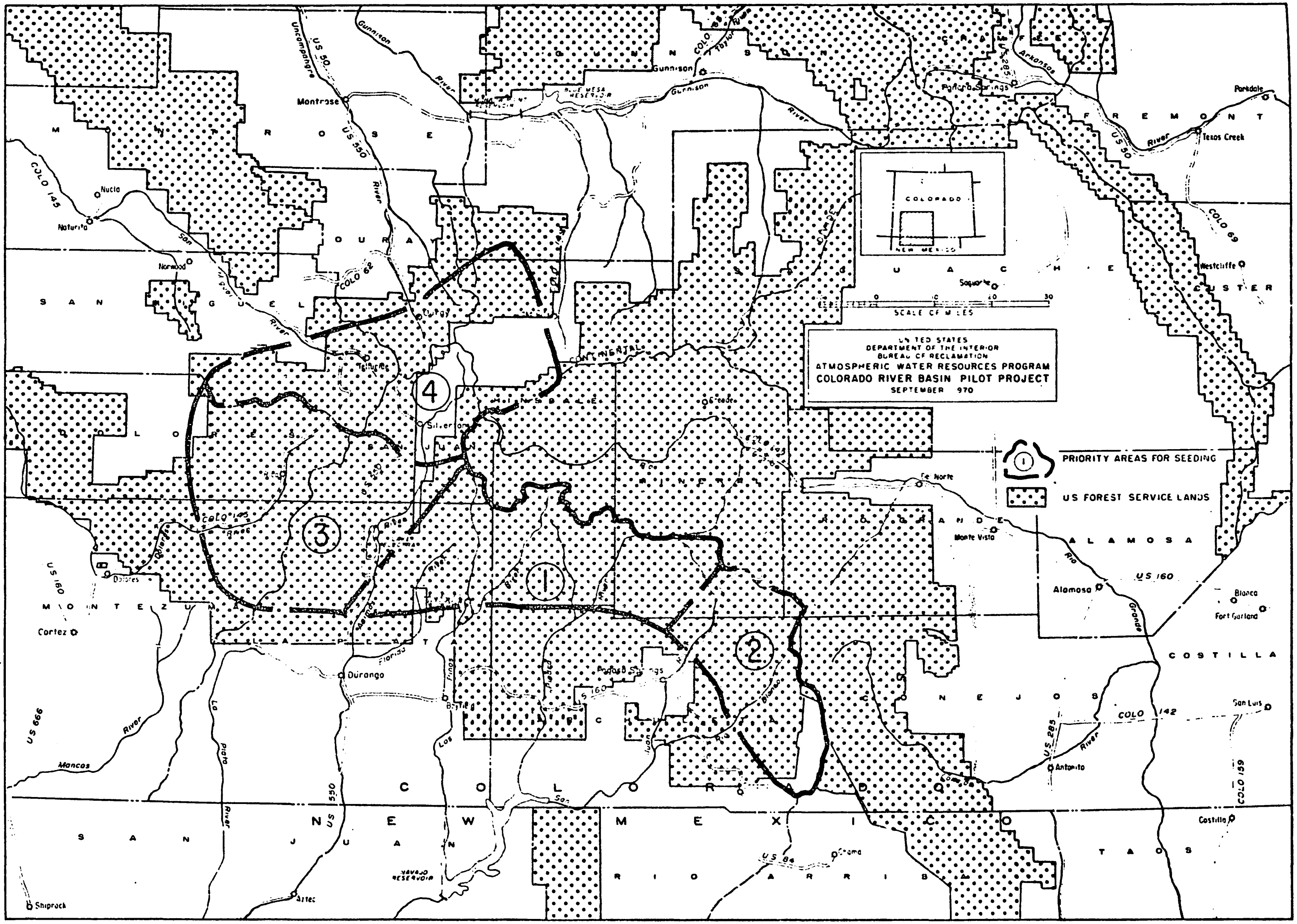

Figure 2-1. Colorado River Basin Pilot Project Area

The initial target area, beginning with the 1970-71 winter season, will be Subareas 1 and 2, the area east of Durango, Colorado, bounded by the Continental Divide and the New Mexico state line. This area covers about 1,300 square miles and includes the Wolf Creek Pass area where the Colorado State University experiment was carried out between 1965 and 1969. The major efforts and the contractors involved are presented in Figure 2-2.

2.4 PROJECT DESIGN CONCEPTS

The project is designed to provide a full, large-scale test of seeding techniques and equipment used at the Climax and Wolf Creek Pass experiments. Newer developments will not be included so that a definite level of existing technology can be tested. Project design and equipment will remain essentially unaltered during the project period. Other pilot projects can be implemented to test new developments when solid evidence of improved seeding results or efficiency are obtained.

This project will concentrate on evaluating the additional precipitation resulting from large-scale seeding. Emphasis will also be placed on studying the associated social and environmental problems of seeding and the total operational costs of seeding. Present plans provide limited observations to learn more about the physical and dynamic processes involved in the atmosphere between the release of silver iodide from the generator to measurement of snow on the ground. Supplemental observations have been proposed to utilize the opportunities provided by large-scale seeding for studying and increasing man's knowledge of seeding processes.

2.5 PROJECT INSTRUMENTATION

An extensive instrumentation system (Figure 2-3) has been installed to evaluate the seeding effects and monitor weather conditions. Additional instrumentation will be installed prior to seeding.

Project instrumentation and communications systems include:

- 3 high altitude, high accuracy stream gages
- 3 remote mountain top weather stations
- 6 remote weather stations at generator sites
- 5 radio repeaters

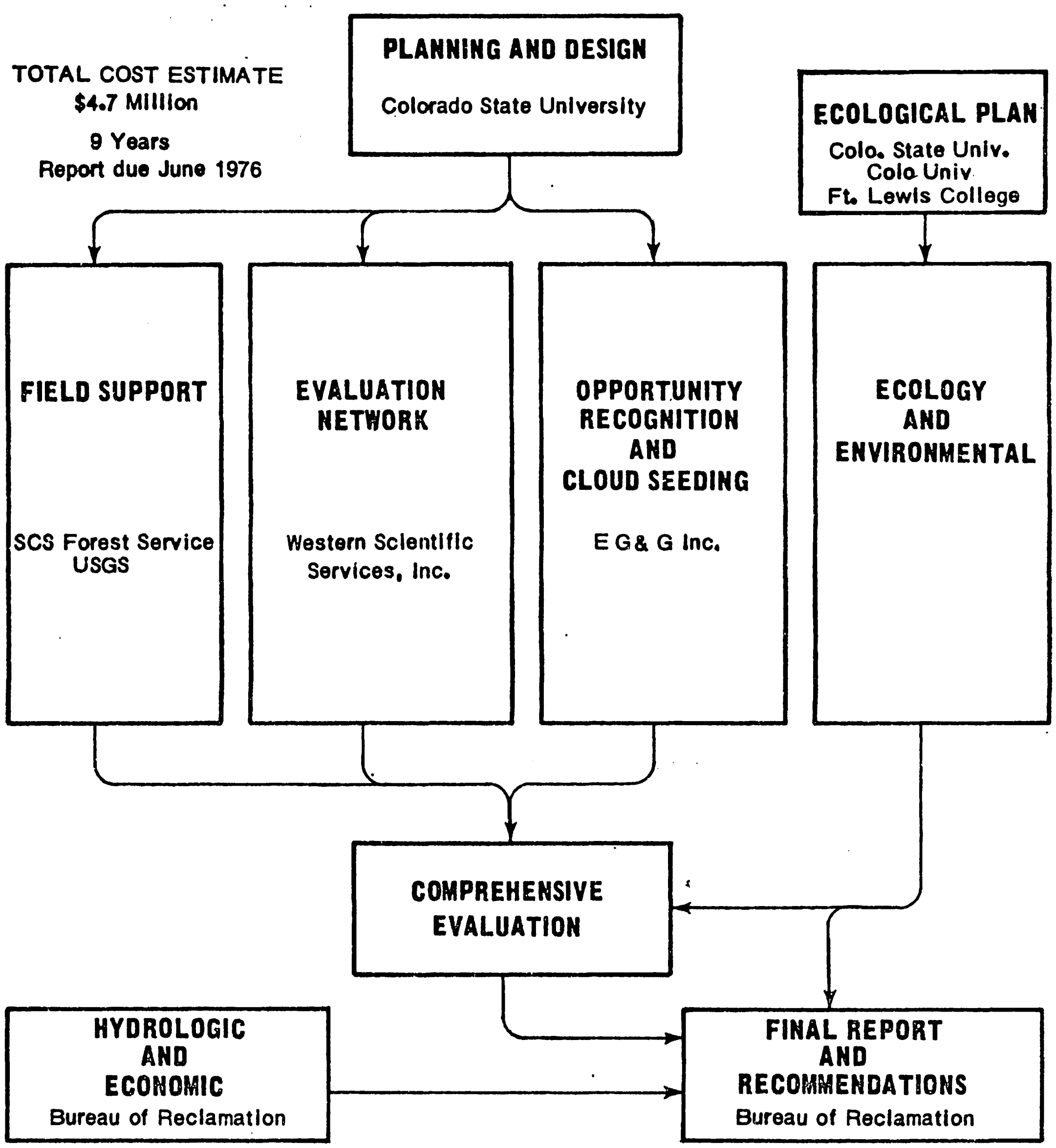

Figure 2-2. Contractors for Major Efforts, Colorado River Basin Pilot Project

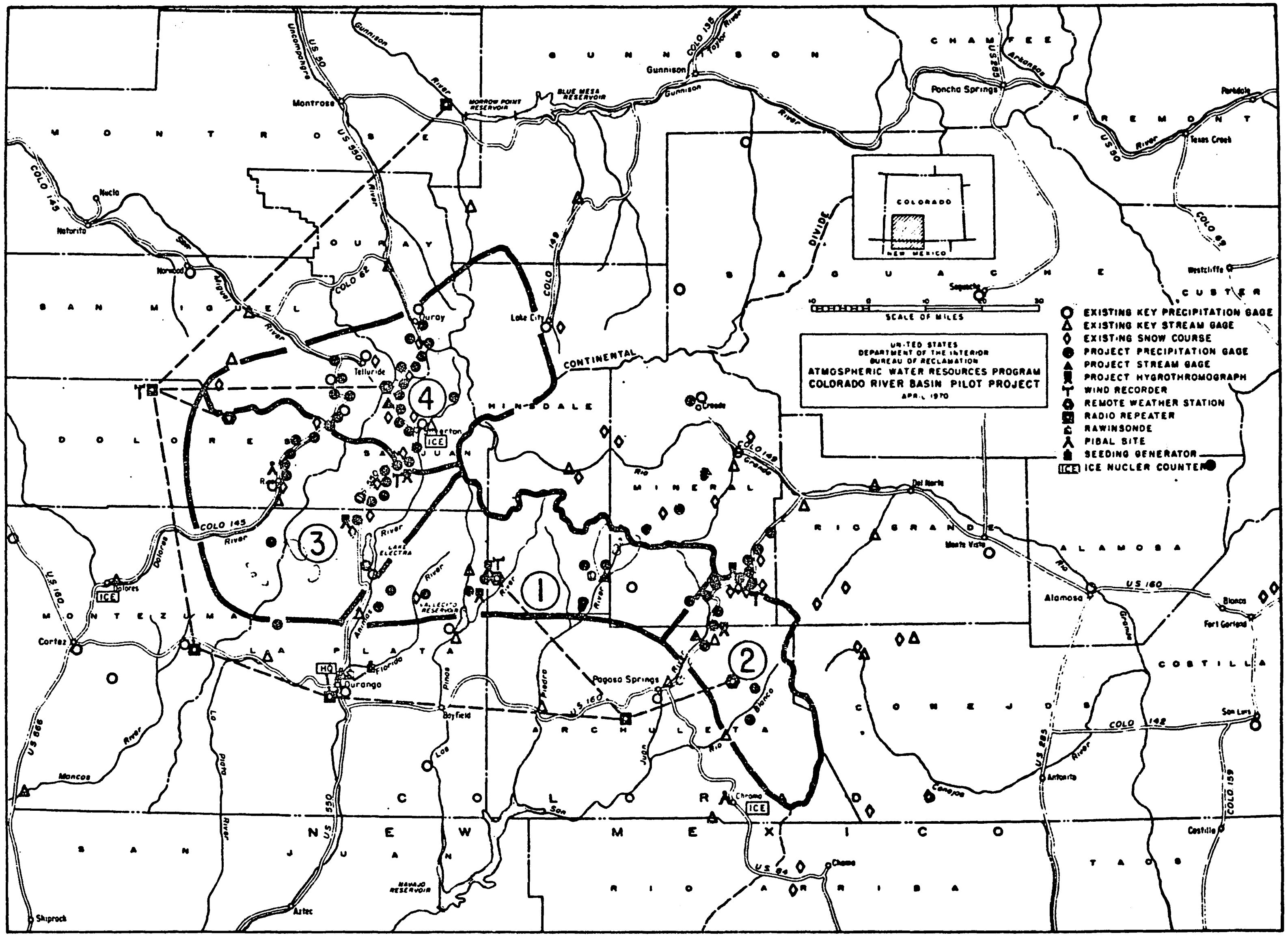

Figure 2-3. Instrumentation System

34 recording precipitation gages
32 nonrecording precipitation gages
1 rawinsonde (upper air soundings)
2 pibal (winds)
4 mountain wind recorders
6 hygrothermograph sites (temperature and humidity)
8 ice nuclei counters
4 snowflake replicators
3 telemetered snow pillows
1 central control and PDP-8 computer for data processing
Special avalanche and ecological instrumentation

In addition to project instrumentation, additional readings will be taken at 35 key existing Soil Conservation Service snow courses and at 28 existing Weather Bureau stations. Addditional water quality and sediment measurements will be made by the Geological Survey at five sites. The communications system installed will provide weather data relay from the telemetered sites, radio control of generators, and emergency communications for crews operating in remote areas.

2.6 SEEDING RESTRICTIONS

An important element of the project plan is the suspension of seeding during situations which may have pronounced detrimental effects on the public and environment in and near the project area. Seeding will be suspended when:

1) The snowpack exceeds 150 percent of long-term average.
2) Severe storm conditions exist or are forecast.
3) Severe avalanche conditions exist or are forecast.
4) Various other critical situations exist as appraised by other Federal or state agencies.

Chances are that about 1 year out of 5 could have suspensions in effect during most of the season.

2.7 EXPECTED RESULTS

Even with seeding of only half the suitable storms, an average precipitation increase of 16 percent in a typical year is expected (see Table 2-1). This

TABLE 2-1. BUREAU OF RECLAMATION PRELIMINARY ESTIMATES OF PROJECT SEEDING RESULTS*

<u>In the SAN JUAN Mountains</u>

About 90 Snowfall Days in Typical Winter = 24 inches (water equivalent)

50 days unsuitable for Seeding = 10 inches
40 days suitable for Seeding = 14 inches
Average 15% decrease from Seeding unsuitable days
Average 55% increase from Seeding suitable days

If Seeding on all snowfall days (as Wolf Creek Pass Experiment)

10 inches from 50 unsuitable days with 15% decrease	= 8.5 inches
14 inches from 40 suitable days with 55% increase	= 21.7 inches
	30.2 inches

an average net increase of 6.2 inches or about 25% overall

Pilot Project with randomization and restrictions
Only Seed about half or 20 of the suitable days

10 inches from 50 unsuitable days (no seeding)	= 10.0 inches
7 inches from 20 suitable days (no seeding)	= 7.0 inches
7 inches from 20 suitable days Seeded with 55% increase	= 10.8 inches
	27.8 inches

an average increase of about 3.8 inches or about 16% overall

Possible with Seeding on all suitable days (Operational Project)

10 inches from 50 unsuitable days (no seeding)	= 10.0 inches
14 inches from 40 suitable days Seeded with 55% increase	= 21.7 inches
	31.7 inches

an average increase of 7.7 inches or about 32% overall

* Bureau of Reclamation, Atmospheric Water Resources Program Manuscript, 1970: The Colorado River Basin Pilot Project

amounts to about 3.8 inches of precipitation annually or about 30-40 additional inches of snowfall. Increases in individual storms may reach 100 percent.

In Subareas 1 and 2, the 16 percent increase due to pilot project seeding should yield an average of 250,000 acre-feet of additional streamflow annually.

2.8 LEGAL, ECONOMIC, AND ENVIRONMENTAL CONSIDERATIONS

While much active support and acceptance of the project have been evidenced in the area, strong objections have also been raised. Farmers, ranchers, and those with water resources interests generally support the project because of the additional water supplies and associated benefits from the project and possible future operations. Objections are generally raised by those with naturalist interests and those within the project area whose livelihood is not dependent on water and who live where snow is a hindrance or danger.

Petitions have been circulated requesting a court injunction against the project, but no definite legal activity has yet occurred. Injunction or suit against the Bureau of Reclamation and its contractors has also been threatened by a local lumbering company. With the opposition to the project, claims for real or alleged damages are very likely once seeding begins. Studies to help define ownership of the new waters produced by cloud seeding and their regulation within existing compacts are another legal consideration. The key to many legal questions appears to be a positive, acceptable evaluation of the snowfall and waters actually produced by seeding.

Partially because of these problems, subareas 3 & 4 were deferred from inclusion in the initial target area. An extensive avalanche study program will be undertaken with the cooperation of the Forest Service to determine the effect of seeding on avalanches and to help avalanche forecasting.

An important part of operational application decision-making will be an analysis of the value of the new water produced and of the net benefits it would make possible. Side costs or dis-benefits are likely, including damage reimbursement and environmental protection. Comprehensive economic studies and cost-benefit analyses will be part of the project.

Many ecological questions have been raised on effects of increasing snowpack. A comprehensive ecological study will be made to monitor and study these effects. Wildlife, fishery, and plant ecology could be affected although pronounced effects are not anticipated. The ecological investigations will be based on a study plan prepared by Colorado State University, Colorado University, and Fort Lewis College.

CHAPTER 3
OPERATIONAL PLAN

The initial target area for the project consists of subareas 1 and 2 (Figure 2-1), containing 1300 square miles. Most generators are located in the area indicated and are typically 20 - 45 miles southwest of the target area.

3.1 RANDOMIZATION AND SEEDING CRITERIA

Although the pilot project is a full scale test of operational type cloud seeding techniques, seeding was done on a random basis to allow scientifically sound and comprehensive evaluations and to provide increased learning opportunities. A randomized schedule of 400 events was developed in advance by the Statistical Laboratory at Colorado State University to give a 50-50 split of seeded versus non-seeded experimental days in intermixed blocks of 10 - 40 days. Numbered sealed envelopes containing the random seed/no seed decisions for an entire operating (winter) season were furnished EG&G prior to the start of the operating season. The 50-50 split with block randomization will have several advantages in the subsequent statistical analysis planned for the project.

3.1.1 Definition of an Experimental Day

A 24-hour period from 1800Z to 1800Z constitutes an experimental day (also called an experimental period). The operation of the seeding system and studies of the meteorological network were oriented to the experimental day. A declaration of an experimental day is based on the 1600Z forecast and there is no provision for a later startup or change. An experimental day was declared based on the morning forecast when the following criteria were met:

1) Precipitation of 0.01 inch or greater is forecast for anywhere in the project target areas during the 1800Z to 1800Z period.
2) Five hundred mb temperature of -23°C or warmer is forecast to exist over the project target areas at least 12 hours during the 1800Z to 1800Z period.

3) Seven-hundred mb winds are forecast to be toward the mountain slopes of the project target areas (approximately 150° through 300°) during the period when 500-mb temperature is -23°C or warmer.

3.2 SEEDING OPERATIONS

On randomly determined experimental days, seeding was performed using a variable seeding rate based on the Climax model. Effective seeding rates were determined by the forecast cloud top or forecast 500-mb temperature, and the monitored cloud top or 500-mb temperature during seeded experimental days as follows:

1) -14°C and warmer produces up to 2 x 10^{16} effective nuclei/hr at -15°C per generator site (up to 200 g hr^{-1}).
2) -15°C through -23°C produces 2 x 10^{16} effective nuclei/hr at -20°C per generator site (20g hr^{-1}).

Appropriate generators in the network were operated for seeding the target areas according to wind direction and speed. Generators were started one hour prior to the start of the experimental day or suitable portion of the experimental day, and operations stopped two hours prior to the end of the suitable seeding period. Generators were not operated during periods of nonsuitable seedability within the seeded experimental periods. Suspension criteria were examined in the light of existing conditions during each seeded period, but the suspension criteria were never met and no seeding suspensions were involved during the 1970-71 operational season.

3.3 RECOGNITION AND FORECASTING

A complete weather forecasting and analysis center was established by EG&G in Durango, Colorado, and was manned by professional meteorologists. All of the basic synoptic weather data inputs were available as well as local rawinsonde and meteorological data from the telemetered network for forecasting and monitoring weather conditions. The main recognition and seeding potential forecasts were made each morning by 1600Z utilizing the 1200Z synoptic data input. This section (3.3) details the forecast tools developed and the procedures implemented.

3.3.1 Discrimination of Precipitation and Nonprecipitation Events

Numerous objective studies were undertaken during the summer and early fall of 1970 to aid in the segregation of precipitation days from nonprecipitation days in the target area. Although presented with little special emphasis in the August 1970 Monthly Status Summary Report, one parameter was shown to implicitly take into account almost all of the precipitation and nonprecipitation producing factors; that parameter was the value of the horizontal wind shear normal to the flow at 500 mb as determined by a grid composed of the nearest NWS stations. The project area is very nearly centered in the grid, which includes Grand Junction (GJT), Salt Lake City (SLC), Denver (DEN), Winslow (INW) and Albuquerque (ABQ). For example positive shear (indicative of cyclonic rotation) in southwesterly flow would mean stronger 500-mb velocities at Albuquerque (ABQ) than at Grand Junction (GJT), and negative shear would indicate the converse (see Figure 3-1).

The value of this discovery, perhaps the finest single objective tool ever devised for a geographical region, can be dramatized by the following statistic: of the 1000 plus hours during which precipitation occurred in the project area between 15 October 1970 and 15 May 1971, no more than 10 hours (approximately 1%), were associated with negative shear. Stated even more forcefully, only 10 hours or less of precipitation "contaminated" the nearly 4000 hours of negative shear value obtained from the grid network.

In addition, the onset and termination of precipitation activity, regardless of whether the flow was northwesterly or southwesterly and regardless of curvature, was also in agreement with the development of positive and negative shear, respectively. Of course, due to the dynamic and thermal properties of the transient waves, the scale of activity in area, depth of cloud, and amount of precipitation were markedly different for the two flow directions.

Cloud type and distribution also tended to have specific characteristics associated with positive and negative shears. In fact, the clue to the precipitation dependence on the shear was marked by an historical study of the NMC hemispheric surface synoptic maps (prepared 4 times daily) in conjunction with 500-mb hemispheric maps prepared twice daily. The observations obtained from these maps tended to agree with what was observed during the past season in the project area. For example, negative shears in westerly or southwesterly flows were accompanied

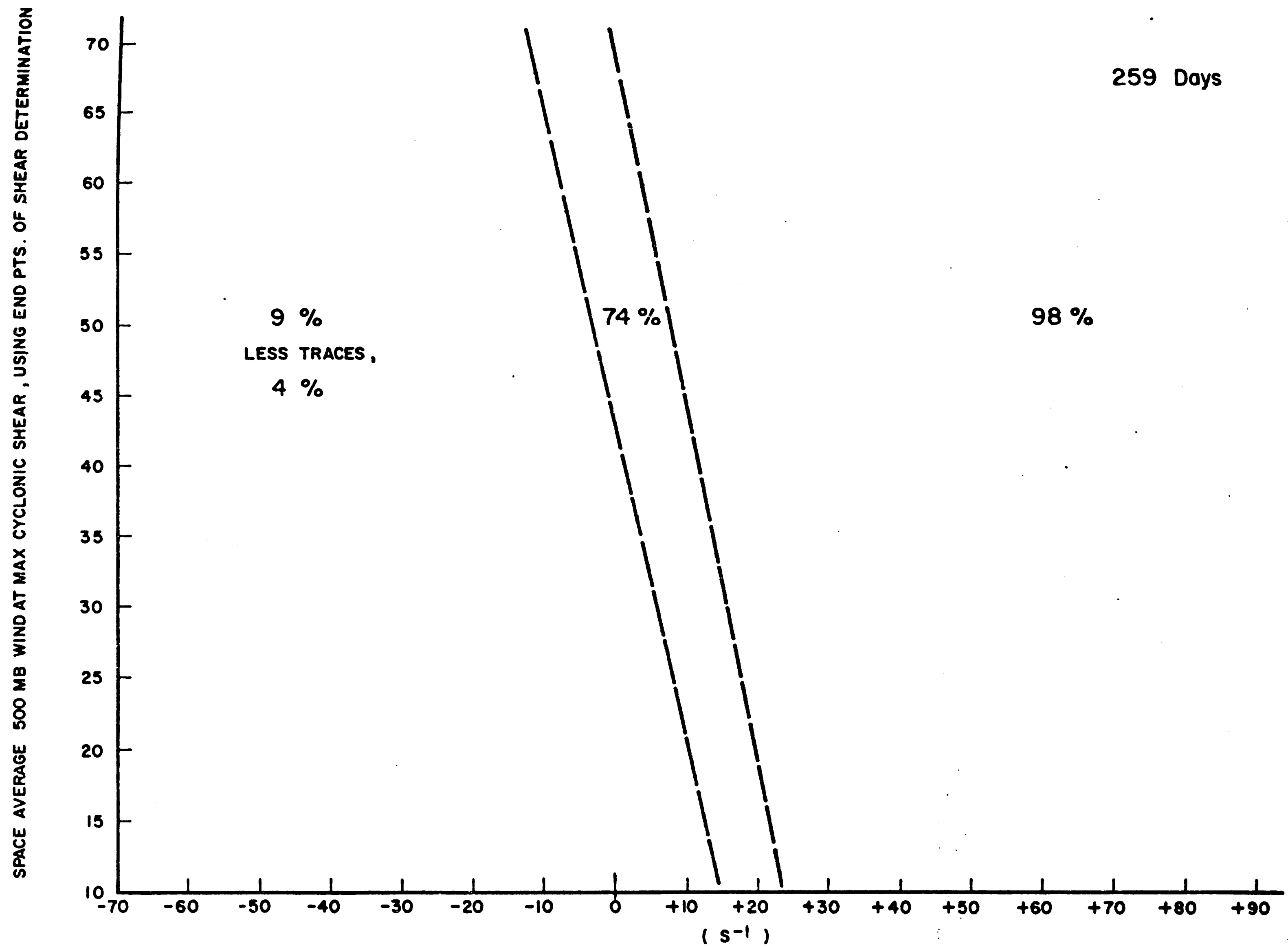

Figure 3-1. Maximum Cyclonic Wind Shear (S-1) at DRO During Preceding 24 Hours

frequently by high and middle clouds, especially lenticulars, and occasional Cu humilis fragments. The development of positive shear for these same flow directions was characterized most often by lesser amounts of cirrus, almost no lenticulars (but much more As and lower, heftier forms of Ac), markedly greater distribution and depth of Cu and Sc, and frequent occurrence of Ns.

Northwesterly flow on the other hand was characterized frequently by no clouds whatever in negative shear flows, while positive shear flows were accompanied by only low, nearly always glaciating Sc and shallow Cu with precipitation. It was not unusual, however, to have extensive cloudiness and precipitation on the northerly and northwesterly facing slopes of the project area during these periods when activity was absent elsewhere.

Although the preponderance of hours with some precipitation was qualitatively judged as overwhelming, it should also be recorded that not every hour of positive shear was accompanied by precipitation. Therefore, positive shear can not be termed a "necessary and sufficient condition," it appears to have all the earmarks of a condition which is "necessary" except in very rare cases.

These rare cases of shear criteria failure seem to be solely associated with exceptionally warm air masses originating from the subtropical Pacific. They are characterized by 500-mb temperatures between -10 and -15°C and a broad 500-mb current. Consequently, the precipitation system is characterized by not only large water content, but also great depth of liquid water clouds. An example of this is the storm sequence for 31 January to 2 February 1963. These characteristics indicate that such failures may be anticipated to a large degree.

The precipitation of the atmosphere toward upward vertical motion and precipitation on the cyclonic or positive shear side of the tropospheric jet is well documented by such researchers as Yeh (1951)[1] and Reiter (1963)[2] in a well known monograph. However, the discovery of such "black-white" dependence of a geographical region is probably new. Particularly illustrative of this phenomena is the satellite photo for 13 March 1971, Figure 3-2. Low cloudiness and precipitation are located on the positive shear (usually northward) side of the 500-mb wind maximum and pronounced lack of clouds immediately to the negative (or southward) shear side.

Because of the emergence of the positive shear as an objective tool, the forecast problem was subsequently reduced to determining the wind field within the

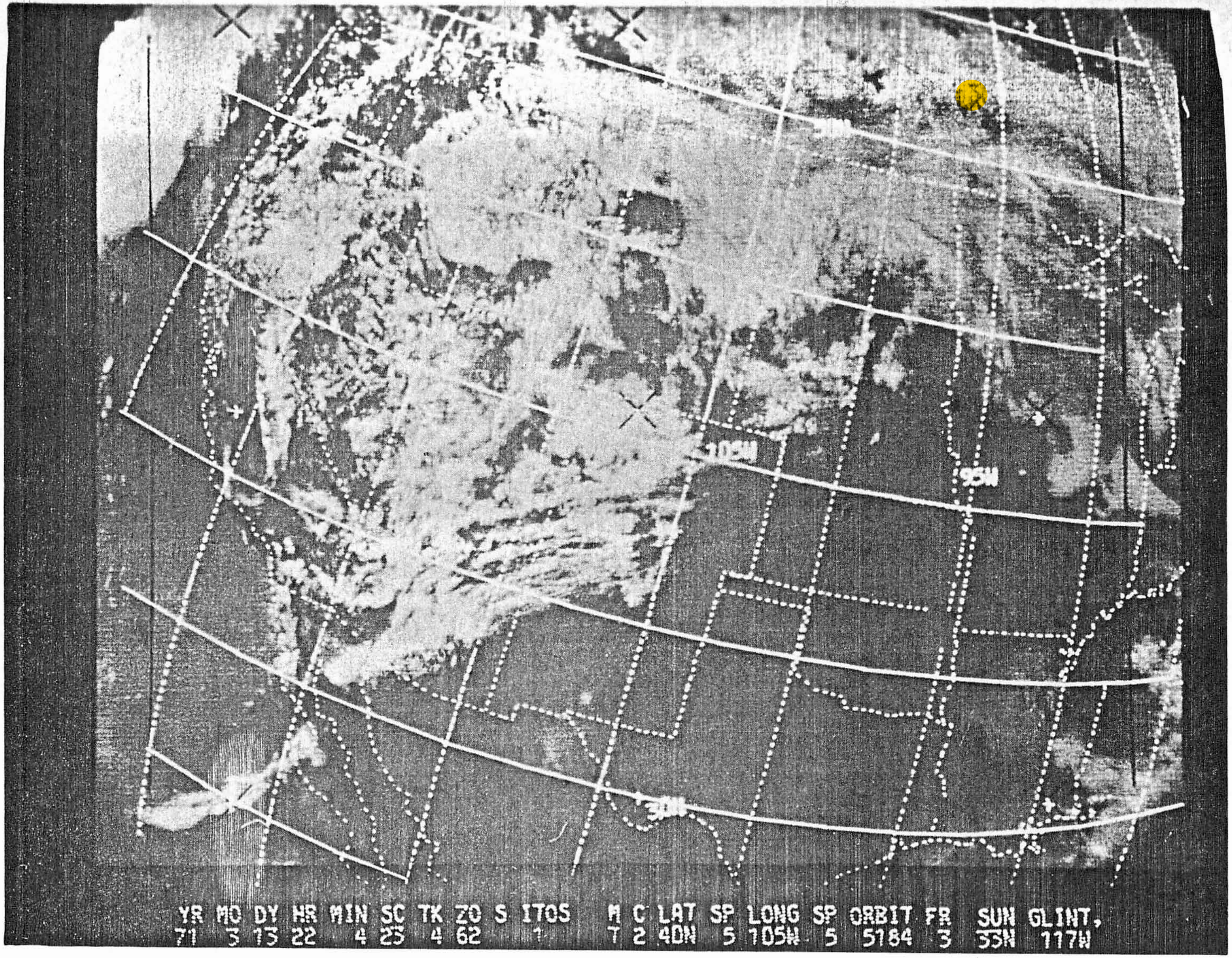

Figure 3-2. Satellite Photo, 13 March 1971

grid for the 0.01 inch or more precipitation event specified in the operating criteria. This was accomplished by a "man-machine" forecast mix of the numerical prognosis distributed by the National Meteorological Center for the 500-mb height and vorticity field utilizing the 6-layer baroclinic and simpler barotropic models. The wind field was ascertained by examination of the stream function spacing on each of the two models. Ironically, the vorticity field forecast was a secondary consideration.

The "man" portion of the forecast included a reservoir of forecasting experience for both Project Forecasters, J. O. Rhea and A. Rangno, including Southwest synoptic weather patterns and a knowledge of certain error characteristics in each numerical model. For example, persistent error characteristics of the 6-layer are overamplification of troughs in the Rockies and Plateau States and under-forecasting of surface cyclogenetic developments in the eastern Pacific – both of which were observed regularly during this past year.

In addition to the shear parameter (detected by A. Rangno), a number of other previously completed studies are reiterated here. Although not as useful as the shear parameters, these studies proved useful in establishing the precipitation climatology of the region and as checks on the amount of precipitation forecast. They are presented in Figures 3-3, 3-4, 3-5, 3-6, 3-7, 3-8, and 3-9.

3.3.2 Quantitative Assessment of Precipitation

To answer the question of how much precipitation was going to fall upon Wolf Creek Pass from a given storm, reliance was placed on the thorough evaluation of flow direction and air mass property interaction with the terrain profiles associated with a specific wind category as developed by J. O. Rhea. An equation developed by Mr. Rhea and used routinely throughout the year greatly improved the stability and, hence, prediction accuracy of the expected precipitation amounts. The equation:

$$\left(\frac{dz}{dx}\right)\left(t\right)\left(q\right)\left(\overline{V}\right) K_1 + \frac{t}{24} K_2 = D$$

where

t = duration of precipitation for a particular wind category.

$\frac{dz}{dx}$ = the terrain rise (or fall) along the streamline.

q = water content in grams per kilogram (mixing ratio).

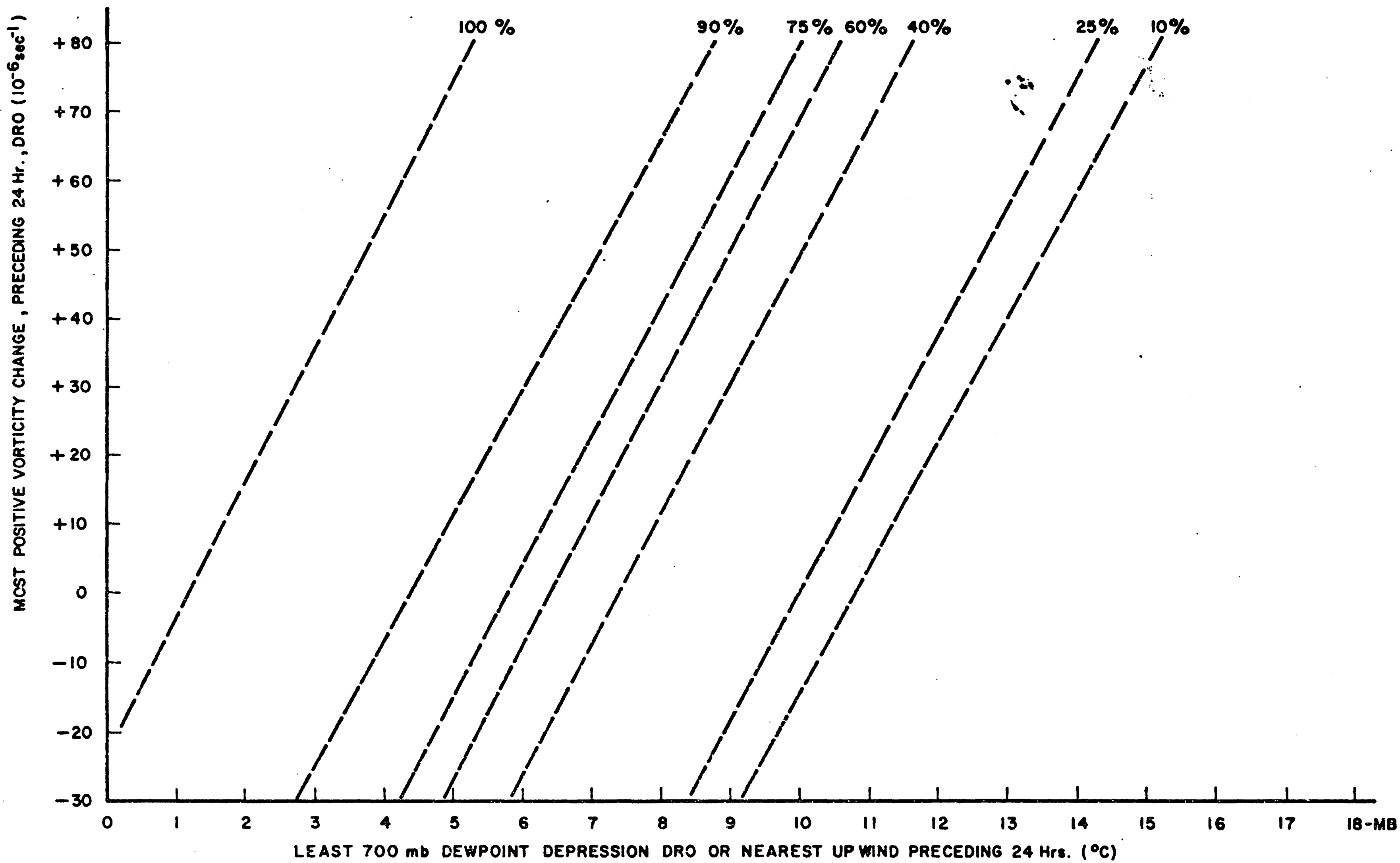

Figure 3-3. Nomogram for Probability of Precipitation (at One or More of Six Stations) in Relation to 500 mb Vorticity Change and 700 mb Dewpoint Depression

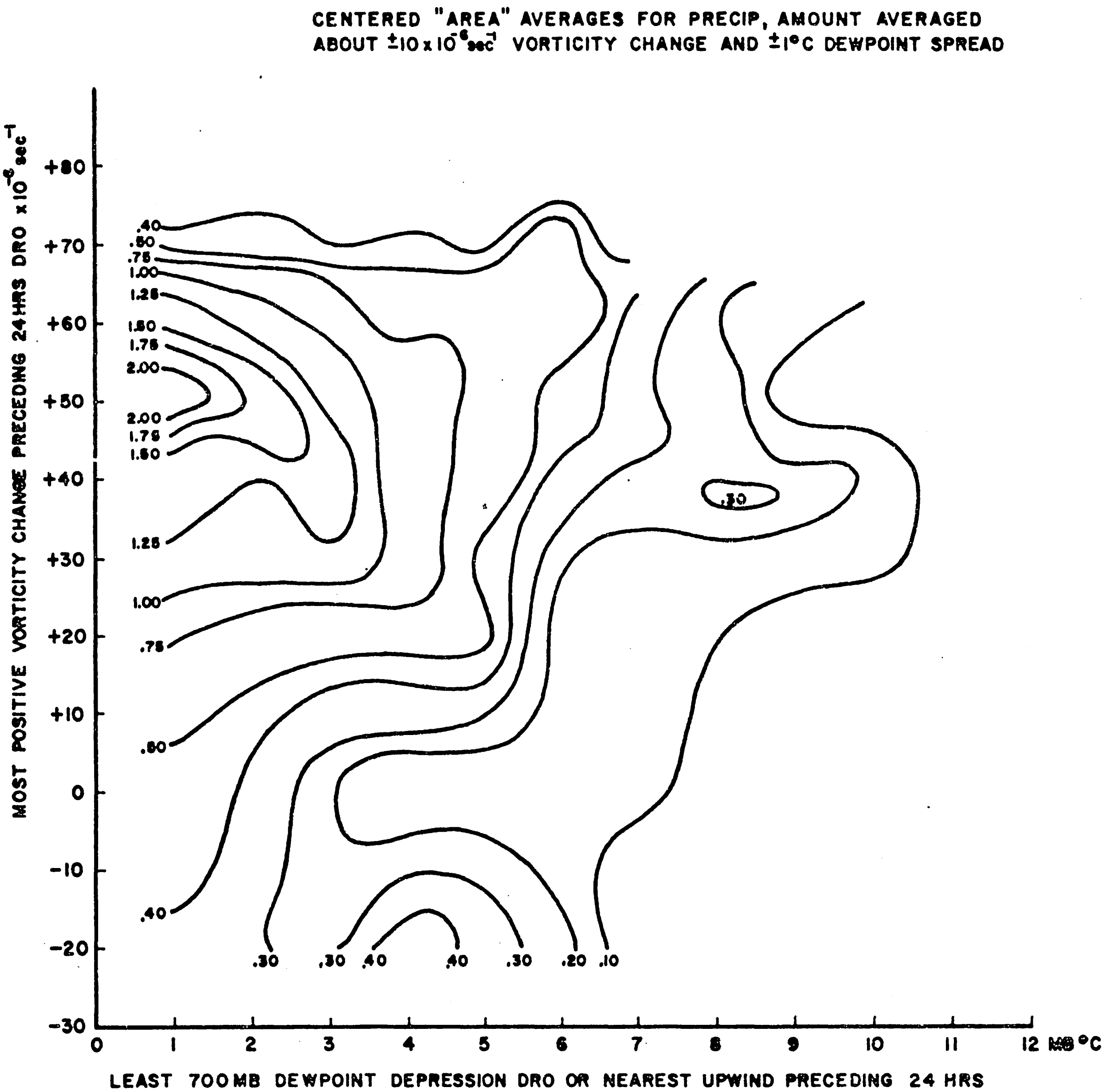

Figure 3-4. Smoothed Six-Station Total Precipitation Average in Relation to 500-mb Vorticity Change and 700-mb Dewpoint Depression

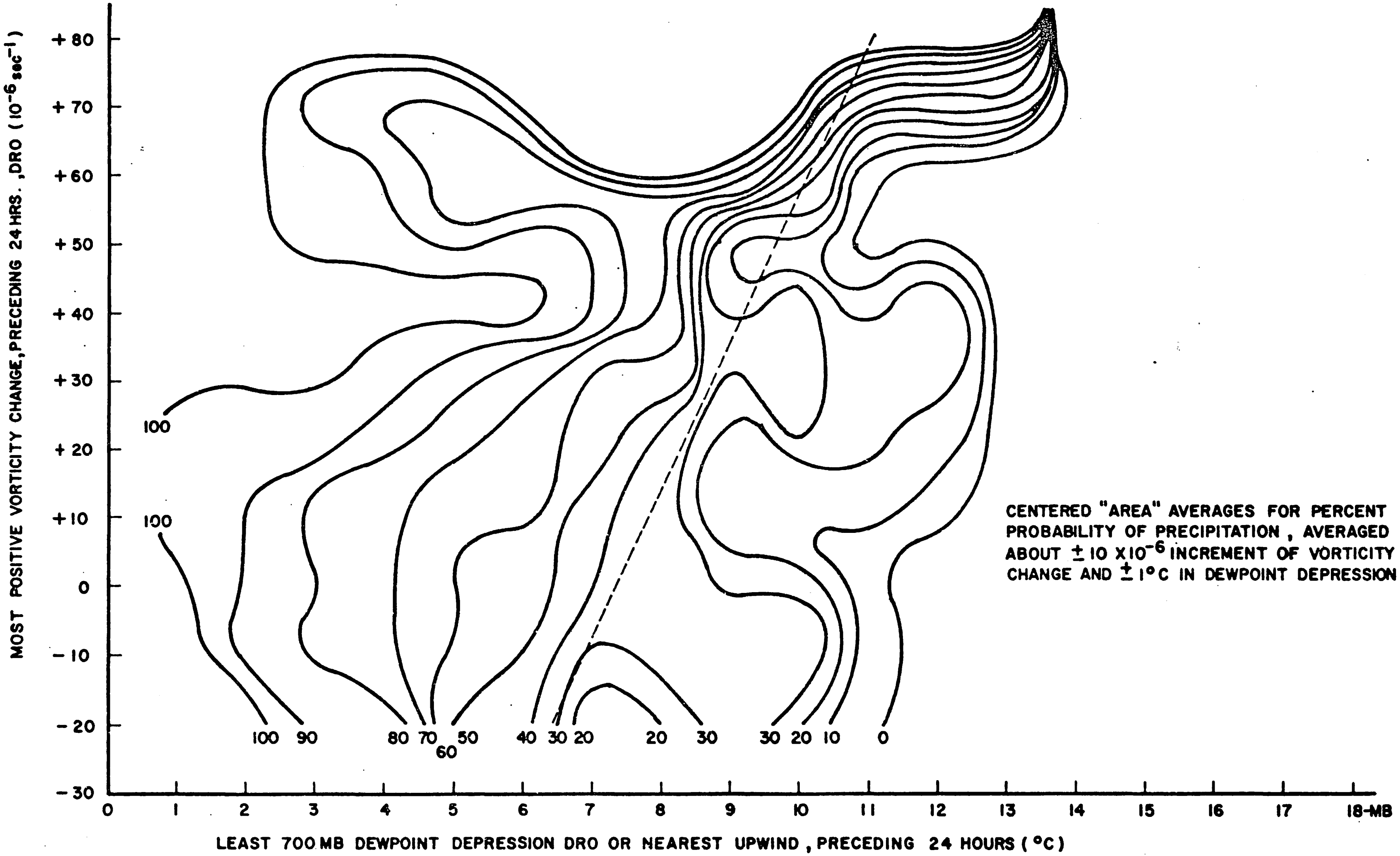

Figure 3-5. Smoothed Probability of Precipitation (at One or More of Six Stations) in Relation to 500-mb Vorticity Change and 700-mb Dewpoint Depression

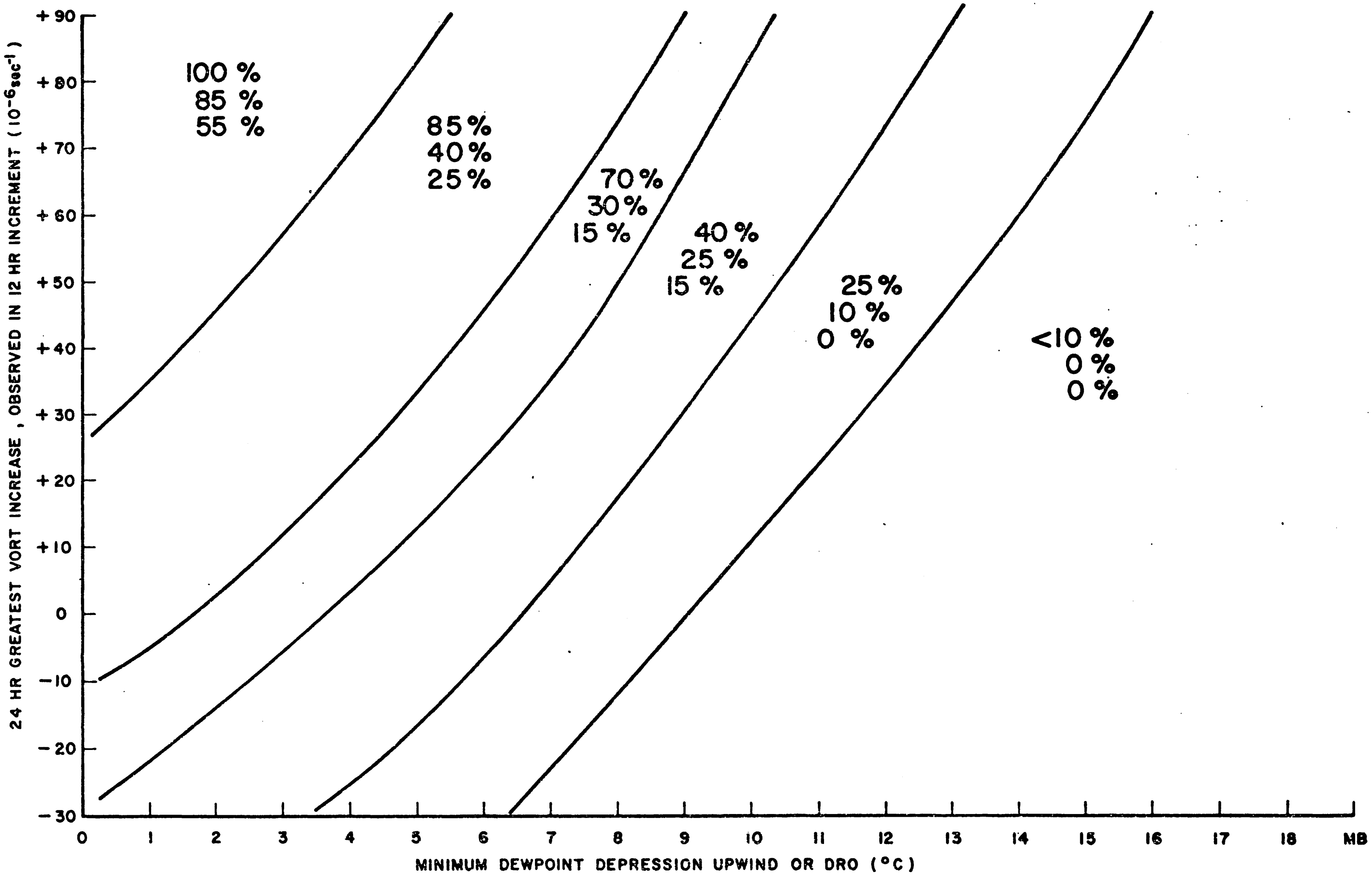

Figure 3-6. Probability of ≥ x Inches of Precipitation at Wolf Creek 1E in Relation to 500-mb Vorticity Change and 700-mb Dewpoint Depression Given that 700-mb Mean Wind Direction is Between 100° and 270° Inclusive

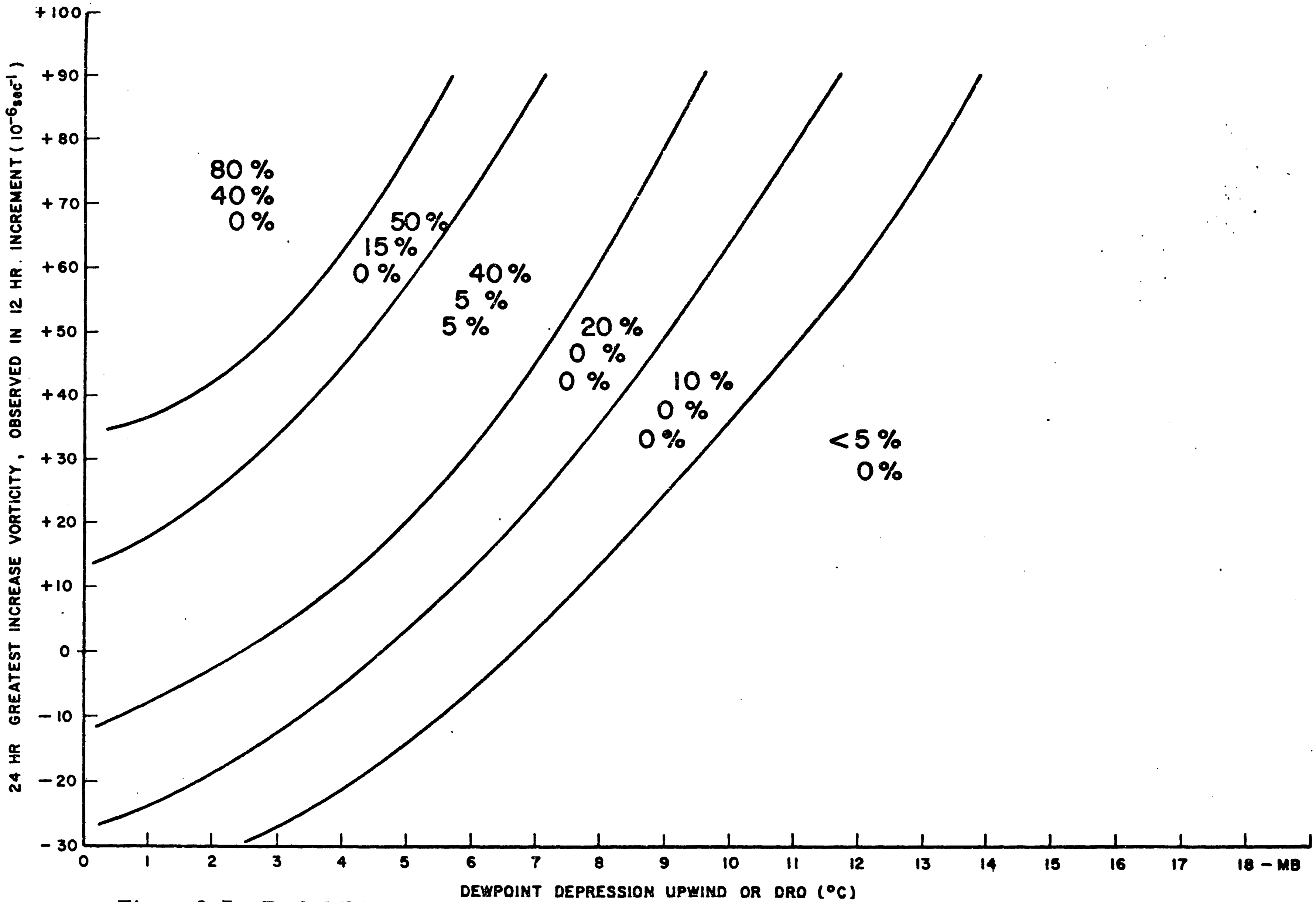

Figure 3-7. Probability of ≥ x Inches of Precipitation at Wolf Creek 1E in Relation to 500-mb Vorticity Change and 700-mb Dewpoint Depression Given that 700-mb Mean Wind Direction is Between 280° and 090° Inclusive

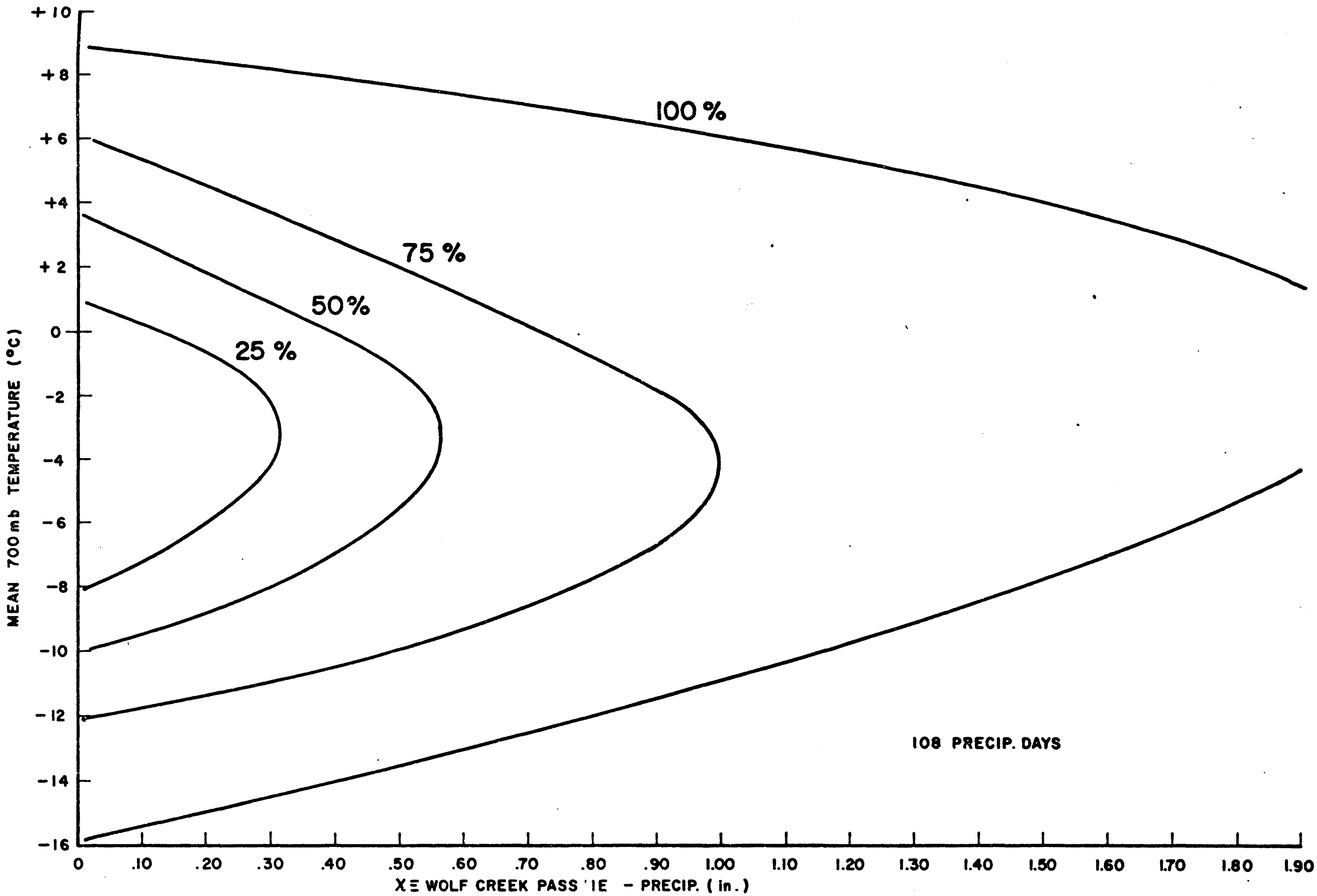

Figure 3-8. Cumulative Probability That 24-Hour Precipitation at Wolf Creek 1E is ≥ x for a Given 24-Hour Mean 700-mb Temperature

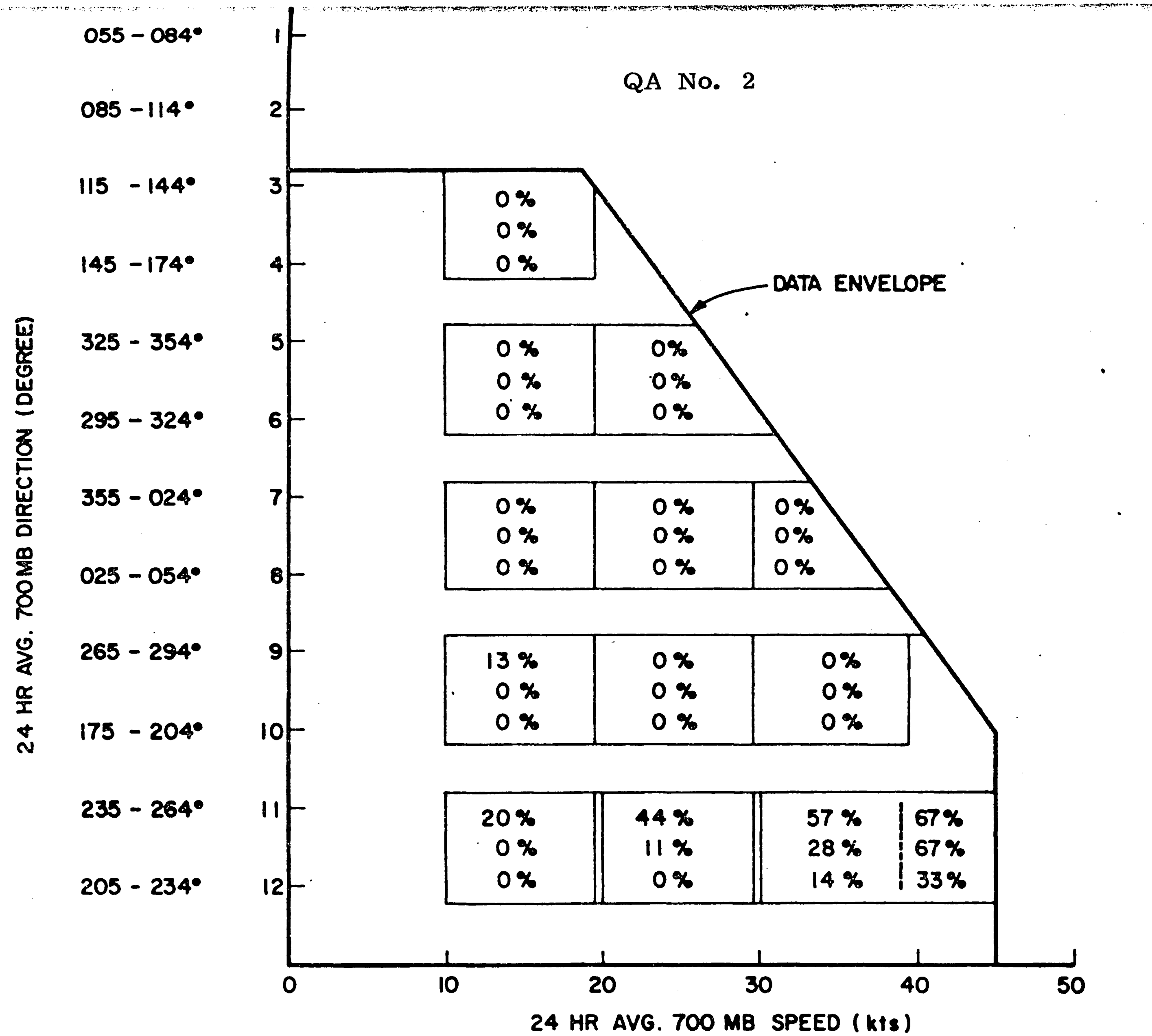

Figure 3-9. PROBABILITY OF ≥0.70", ≥1.00", ≥2.00" (TOP TO BOTTOM) AT WOLF CR. IE

$\bar{V}$ = the mean 700-mb wind velocity for the period of precipitation.

K_1 = constant.

K_2 = constant, representing the contribution of precipitation by nonterrain effects.

D = depth of liquid water in inches.

3.3.3 Precipitation in Relation to 700-mb Wind and Terrain Slope

Wind Direction Dependence of Area Precipitation Patterns

Ridge-Valley winter precipitation ratios range between 2 and 10 to 1 over the Colorado Rockies. Both ridge and valley areas are simultaneously under similar large-scale meteorological influences. It is therefore obvious that the forced mechanical (orographic) lifting of moist air as it approaches the ridges strongly dominates the large-scale vertical motions field in establishing the area precipitation pattern.

The magnitude of the orographic lifting is roughly determined by:

$$w \cong \hat{V} \cdot \frac{dz}{dx} \vec{i},$$

where

$$\hat{V} = \frac{dx}{dt} \vec{i} + \frac{dy}{dt} \vec{j}.$$

$$x = \text{direction of the fall-line and } \vec{i} \cdot \vec{j} = 0.$$

This, coupled with the fact that the largest concentration of condensate is possible in the warmer, lower layers, logically leads to the importance of the degree of alignment of low-level winds with the terrain slope in setting the mesoscale precipitation patterns (and the variations thereof). Superposition of effects from multiple ridges with differing slope vectors, however, complicates the problem.

An examination to determine the degree to which wind-slope alignment effects could be delineated was made. The study covered the periods November-March for 12 seasons (1955-1967). 20 ESSA climatological data precipitation stations in or near the project area were used. (Only sunset-reading stations were used.)

Twenty-four hour precipitation totals were tabulated for each station, and a precipitation day was defined as one in which measurable precipitation occurred at at least one of the 20 stations. Thus, most of the completely dry days were eliminated.

Vector 24-hour mean 700-mb wind directions at Grand Junction (GJT) were tabulated for each of the days in the resulting set of precipitation days. Twelve 30° direction categories were designated running consecutively clockwise. The limits of Category 1 were 175° to 204°; Category 2, 205° to 234°, etc.

The precipitation day data set was then stratified by direction category. Each station's 24-hour average ($\bar{x}_i$) was computed for each category i (Table 3-1). The ratio $\bar{x}_i/\bar{x}$ (where $\bar{x}$ is the station average overall direction categories) was computed for each station. This ratio is a dimensionless variable and is contourable when plotted on an area map. An example of this technique is presented for Wolf Creek Pass 1 East in Figure 3-10.

Multiple Correlation of Precipitation to Terrain Slope

The degree of importance of terrain slope (computed over various distance scales about the station) was studied by a standard stepwise multiple linear correlation analysis.[3] Prior to invoking this analysis routine, the original set of precipitation data was substratified (within each direction category) into the three wind speed categories of: 1) less than or equal to 12 knots, 2) 13 to 25 knots, and 3) greater than or equal to 26 knots. Wind speeds are again the vector 24-hour mean for Grand Junction. Correlation of precipitation was also made to station elevation. Only the direction categories 1 through 7 were used, due to insufficient sample sizes in the remaining categories. The data set finally used was that for each of seven direction categories which also fell into the 13- to 25-knot wind speed category.

Specifically, the procedure was to compute average elevation along a 30° arc at 10-km increments from the station (both upstream and downstream), out to a maximum distance of 50 km. The resulting directionally dependent elevation profiles for Wolf Creek Pass 1E are shown in Figure 3-11. Table 3-2 lists the set of eight distance scales over which elevation differences were computed and to which precipitation was correlated.

Since both cloud depth and mean temperature (and therefore mean mixing ratio) decrease with increasing direction category (as the wind veers), the multiple

TABLE 3-1

STATION AVERAGE 24 HOUR PRECIPITATION BY 700 mb WIND DIRECTION CATEGORY

	175-204	205-234	DIRECTION CATEGORY										
	1	2	3	4	5	6	7	8	9	10	11	12	Overall
% of Total Precip. Days	4.4	13.3	25.0	22.2	15.4	8.6	6.9	2.4	0.6	0.6	0	0.6	100.0
STATION													
Durango	.263	.287	.149	.047	.026	.020	.045	.151	.042	.363	NO OCCURENCES	.200	.113
Ouray	.120	.128	.161	.097	.130	.165	.197	.192	.082	.278		.300	.127
Ames	.115	.227	.181	.127	.115	.058	.067	.127	.150	.367		.337	.142
Conejos	.055	.021	.004	.011	.014	.029	.020	.029	.015	.120		.050	.015
Cortez	.127	.137	.093	.052	.022	.015	.021	.087	.042	.198		.140	.070
Del Norte	.069	.055	.019	.014	.018	.049	.040	.143	.054	.233		.143	.033
Fort Lewis	.203	.241	.125	.056	.036	.031	.032	.094	.048	.293		.148	.099
Hermit	.178	.120	.083	.035	.033	.026	.029	.057	.130	.263		.463	.072
Ignacio	.136	.172	.080	.042	.017	.031	.047	.065	.016	.248		.123	.069
Mesa Verde	.218	.225	.136	.078	.031	.028	.036	.175	.048	.343		.148	.108
Northdale	.155	.155	.069	.025	.015	.024	.032	.049	.056	.198		.110	.058
Norwood	.075	.117	.082	.062	.043	.038	.049	.092	.114	.145		.198	.072
Pagosa	.211	.139	.164	.060	.033	.036	.050	.138	.056	.178		.288	.100
Rico	.196	.321	.211	.104	.068	.023	.046	.097	.096	.293		.413	.149
Saguache	.042	.029	.015	.014	.017	.026	.015	.084	.008	.255		.120	.022
Silverton	.179	.204	.135	.077	.096	.041	.059	.083	.096	.290		.255	.113
State Turkey	.234	.214	.134	.068	.018	.014	.011	.097	.025	.310		.210	.089
Trout Lake	.177	.214	.267	.168	.187	.066	.048	.135	.230	.400		M	.174
Vallecito	.307	.350	.211	.074	.040	.029	.062	.214	.094	.440		.325	.152
Wolf Creek 1E	.354	.647	.350	.229	.114	.078	.139	.290	.247			.510	.287

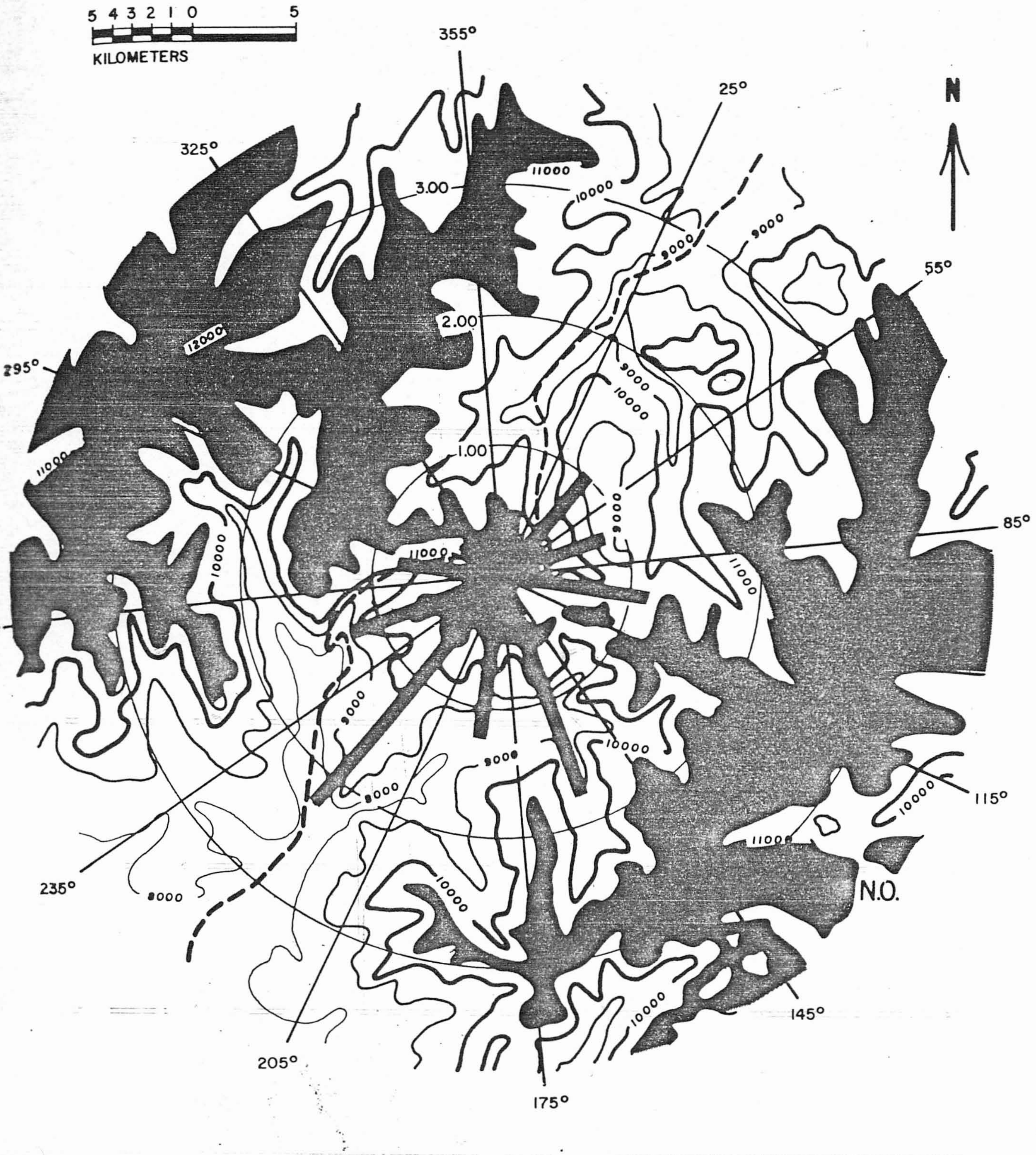

Figure 3-10. POLAR COORDINATE REPRESENTATION OF $\overline{Xi}/\overline{X}$ BY 700mb DIRECTION CATEGORY FROM WOLF CREEK PASS IE

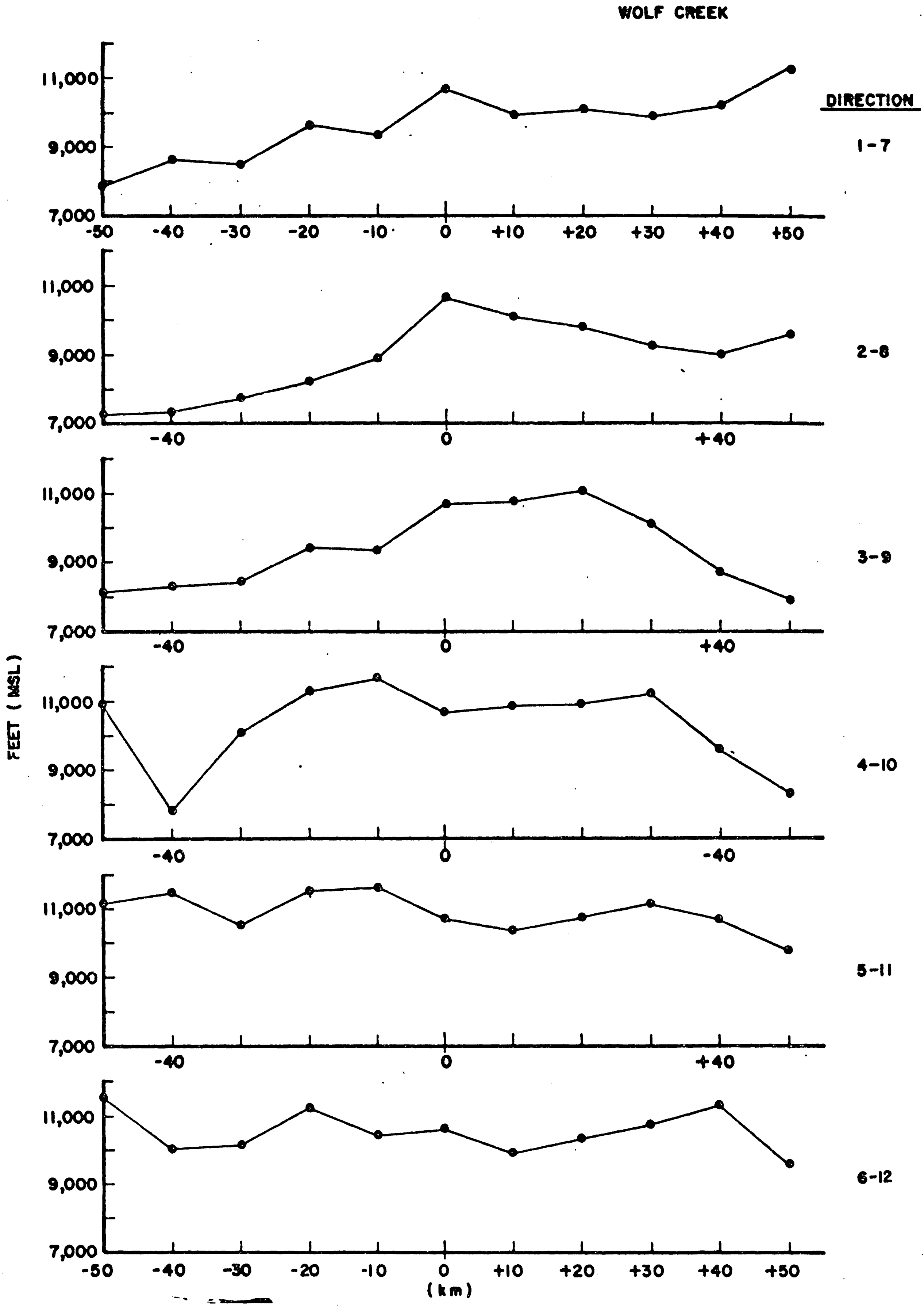

Figure 3-11. Average Terrain Profile Encountered by Air Moving Over Wolf Creek 1E from Left to Right (Right to Left) for Direction Categories 1-6 (7-12)

TABLE 3-2

REGRESSION EQUATION COEFFICIENTS, CORRELATION COEFFICIENTS AND STANDARD ERRORS OF ESTIMATE

700 mb Direction Category	Coefficient for Elevation	Coefficients for End Point Elevation Differences (+ ≡ Downstream, - ≡ Upstream)										
		+10 km, -20 km	0, -10 km	0, -30 km	-10 km, -40 km	-10 km, -30 km	+20 km, -30 km	+40 km, -40 km	-10 km, -50 km	Constant	Sta. Error	r
1	.00000	.00439	-.00986	.00725	-.01178	-.00663	-.00241	.00337	.00812	.10144	.033	.954
2	.00004	-.00097	-.00221	.00168	-.00087	-.00405	.00413	.00189	.00068	-.17973	.033	.970
3	.00001	-.00034	-.00103	.00000	-.00281	.00516	-.00039	.00216	.00000	-.01545	.026	.948
4	.00001	.00073	-.00510	.00535	.00022	-.00387	-.00027	.00034	.00000	-.03387	.009	.983
5	.00001	.00103	-.00140	-.00114	.00140	-.00000	-.00038	-.00120	-.00101	-.03833	.014	.972
6	-.00003	.00185	-.00028	-.00429	.00000	-.00000	.00086	-.00026	.00213	.20108	.028	.893
7	-.00004	.00174	.00000	-.00553	-.00589	.00917	-.00349	.00298	.00324	.32571	.028	.894
All Directions	.00000	.00059	-.00009	-.00028	-.00011	.00020	-.00003	.00032	-.00004	-.0479	.034	.800

correlation analysis was performed for each of the seven direction categories. Sample size in each case was 15 (five of the 20 ESSA climatological stations used in the original study were eliminated on the basis of data quality). The 15 stations used are listed in Table 3-3.

Remarkably high multiple correlation coefficients were obtained. Regression equations, multiple correlation coefficients and standard errors of estimate are shown in Table 3-2 for each of the seven direction categories. The lowest multiple correlation coefficients (0.89) occurred when the wind direction was from NNW to NNE, which corresponds to cases of least representativeness of the Grand Junction 700-mb wind to the wind field over the San Juan Mountain region. Conditions of WNW to NW flow yielded the highest correlation (0.97 to 0.98), which also corresponds to the least complicated wind and precipitation patterns over the San Juans.

The next step in the procedure was to assume that for the single correlation of precipitation to the elevation change from 10 km downwind to 20 km upwind of the station, the precipitation value of the best fit regression line existing for zero elevation difference between 10 km downstream and 20 km upstream represented the non-orographic precipitation component. This value was then subtracted from the average precipitation value for each station (in the wind direction category under study). Secondly, a simplified mathematical formulation of the orographic precipitation mechanism includes the product of mean mixing ratio for the precipitating layer and the terrain slope. Therefore, each elevation difference was multiplied by mean 700-mb mixing ratio existing for the particular wind direction category. With these two modifications to the original data set, all seven direction category samples were used at once (giving a total sample size of 105). The resulting regression equation and the multiple correlation coefficient are listed in Table 3-2.

From the nature in which the original precipitation data were computed (i.e., 12-year means of 24-hour precipitation), results from this study cannot be employed per se for predicting 24-hour precipitation on an individual event basis. However, the extremely high multiple correlation to terrain slope yields very valuable clues to 1) the building of more sophisticated orographic precipitation models, 2) the selection of optimum target/control areas, and 3) choosing other seeding effect evaluation methods.

TABLE 3-3

STATIONS USED IN STEPWISE MULTIPLE REGRESSION ANALYSIS

STATION	NO.	ELEVATION (ft)	STATION	NO.	ELEVATION (ft)
Ames	01	8701	Northdale	09	6693
Cortez	02	6177	Norwood	10	7017
Del Norte	03	7884	Ouray	11	7740
Durango	04	6550	Pagosa Spgs.	12	7238
Ft. Lewis	05	7595	Rico	13	8842
Hermit	06	9001	Silverton	14	9322
Ignacio	07	6424	Vallecito	15	7650
Mesa Verde	08	7070			

Precipitation Probability by Wind Direction

The original data tabulations contain the information necessary to determine the percentage contribution to total precipitation at each site by direction category. This information was compiled and is presented for Wolf Creek Pass 1E in Figure 3-12. Two-thirds of the total precipitation at this site occurs with 700-mb winds between 175° and 264° (30% occurs in the 205°-234° sector) and another 17% is added between 265° and 294°. Sixty-one percent of the total occurs in the sector 205°-264° on only 38% of the precipitation days, or on four to five days per month.

The probability of precipitation ≥x (some designated value) was also computed for each station by direction category. Values of x were 0.1, 0.3, 0.5 and 1.00 inches. Table 3-4 shows these probabilities for selected stations.

3.4 AVALANCHE APPRAISAL

The objective tools for predicting avalanche occurrence presented in this report are perhaps the most refined tools possible for interrelating of snow physics and the structural characteristics of avalanches with the crude synoptic scale meteorological data available. Although these tools were not put to their fullest test because of the snowfall deficit of this past year, it nevertheless is impressive that no avalanches were predicted along Wolf Creek Pass, and none occurred.

The following sections outline the evolution and conclusion of these studies conducted by J. O. Rhea.

3.4.1 Initial Data Sources

Seventeen years of avalanche data for Wolf Creek Pass were made available to EG&G by the Forest Service office in Fort Collins. Similar data were also obtained from the Highway Department in Durango.

3.4.2 Avalanche Frequency

From a study of the Wolf Creek occurrence data, only 20 discrete natural avalanche events (days with one or more avalanches) were observed in the 17-year record. Nineteen of these occurred between 16 December and 28 February. The other was on 25 November 1965 and was accompanied by 80 knot, 500-mb southwesterly winds and 40 knots at 700 mb.

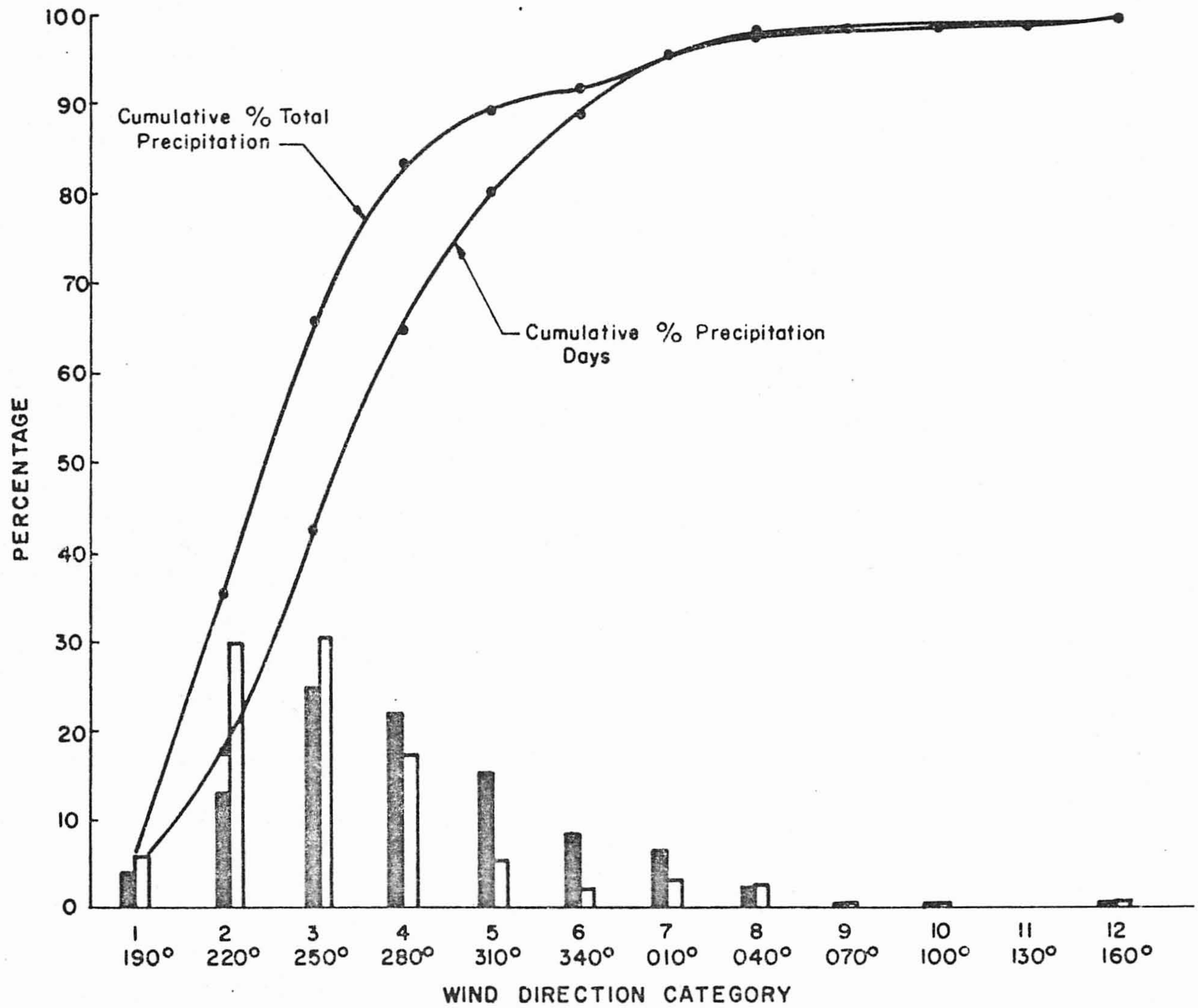

Figure 3-12. FREQUENCY AND IMPORTANCE OF PRECIPITATION AT WOLF CREEK PASS IE VS. 700mb WIND DIRECTION

TABLE 3-4

CLIMATOLOGICAL % PROBABILITY OF PRECIPITATION ≥X BY 700mb WIND DIRECTION CATEGORY FOR SELECTED STATIONS

PRECIPITATION	DIRECTION CATEGORY										
≥X	1	2	3	4	5	6	7	8	9	10	12
DURANGO											
X = 0.1"	67	68	43	19	10	10	12	43	20	100	67
0.3"	46	34	23	5	4	0	7	21	0	100	33
0.5"	0	19	13	1	0	0	0	21	0	67	33
1.0"	0	8	1	0	0	0	0	0	0	0	0
OURAY											
X = 0.1"	34	53	44	39	50	61	61	72	40	100	67
0.3"	19	17	12	10	14	16	25	17	0	50	67
0.5"	7	4	7	1	5	2	2	11	0	0	67
1.0"	0	0	1	0	0	0	0	0	0	0	0
RICO											
X = 0.1"	50	74	68	42	32	10	18	44	40	100	75
0.3"	23	35	38	12	9	0	2	19	0	75	75
0.5"	14	17	24	7	2	0	0	0	0	0	25
1.0"	4	6	4	1	0	0	0	0	0	0	0
WOLF CREEK PASS 1 MILE EAST											
X = 0.1"	74	77	63	46	35	39	44	82	67	50	100
0.3"	35	58	46	21	17	29	19	36	33	50	100
0.5"	35	47	27	16	6	22	0	27	33	50	50
1.0"	4	27	11	4	0	0	0	0	0	50	50

Twelve of the events occurred in three years when snowfall was unusually frequent and heavy.

3.4.3 Attendant Upper Air Features and Precipitation

All but three of the avalanche events (those in 1951-52 and 1952-53) were studied in relation to upper air features and precipitation by plotting time sections of 700-mb and 500-mb wind, temperature and dewpoint.

Interesting features observed included the following:

1) Only one avalanche was not associated with 24-hour precipitation (at either Wolf Creek 1E or 4W) of $\geq 0.70''$ on or within one day prior to the event, and this one exception was sandwiched in between two other events, making its right to the classification of "discrete event" somewhat questionable.
2) All but one event were accompanied by 500-mb winds of ≥ 50 knots within 12 hours prior to the event.
3) Only one of 17 events was not associated with an experimental day on or within one day preceding the avalanche event, and it was a loose type snow, accompanied by 500-mb temperatures, too cold for seedability. A 700-mb wind direction was still in the proper envelope.

The three other events occuring prior to our available upper air data records were accompanied by precipitation amounts indicative of southwesterly flow and seedable 500-mb temperature categories. Therefore, it appears safe to say that when an avalanche occurs, there is approximately a 95% probability it will be accompanied by (or immediately preceded by) an experimental day.

3.4.4 Data Stratifying Routines

In studying the avalanche data in relation to tabulated precipitation records, there appeared to be a dependency not only on some threshold values of 24-hour precipitation on or within one day prior to the event, but also on: 1) total precipitation over the previous several days and 2) the frequency of precipitation in the previous several days. (The dependence on several day total is logically related to the need for a substantial amount of unconsolidated underlying snow surface, while the number of days of precipitation implies the need for cloudy weather to prevent settling and strengthening of recently deposited snow.)

Therefore, a three-way joint stratification was attempted in order to refine avalanche occurrence forecasting by probabilistic methods.

Also, snow density and cohesiveness are related to upper air temperature, and the threshold wind required for snow transport is dependent on cohesiveness and density of the snow. Therefore, additional joint stratification on 700-mb wind and temperature was made for the data sample resulting from the above three-way stratification. This stratification was chosen by scatter plotting occurrence and non-occurrence data on a plane defined by 700-mb speed (maximum within preceding 24 hours) and 700-mb temperature (accompanying the maximum speed) coordinates.

Finally, the data sample existing under this five-way joint stratification was further limited to days defined as experimental according to the pilot project seedability criteria.

3.4.5 Resulting Conditional Probabilities of Avalanche Occurrence

If we define:

A = event that maximum 24-hour precipitation, p24, lies between some given limits

B = event that precipitation total past ten days, p10, is above some threshold value

C = event that number of measurable precipitation days in past ten days is ≥ 4

D = event that the data point lies in the half plane above a given line of demarcation on the 700-mb wind speed (v), temperature (t), plane

E = event that an experimental day exists

X = avalanche event

then we can write, for instance:

$P(X|ABCDE)$ = Y, meaning the probability of an avalanche given that A, B, C, D and E all exist simultaneously is Y.

Now, first restricting data to the 16 December - 28 February period, setting the limits of A = 70" $\geq$p24 $\geq$0.99", B = p10 $\geq$1.75", and from the scatter plot on 700-mb speed, temperature coordinates determining D = $(v - 2.0t \geq 45)$ we find:

$$P(X|A) = 5/40\ (0.125)$$
$$P(X|ABC) = 4/20\ (0.200)$$
$$P(X|ABCD) = 4/9\ (0.444)$$
$$P(X|ABCDE) = 4/7\ (0.571)$$

Next, defining $A = 1.00'' \geq p24 \geq 1.99''$, $B = p10 \geq 2.50''$, and $D = (v - 2.5t \geq 35)$ (where t is in °C and v is in knots), we find:

$$P(X|A) = 7/29\ (0.241)$$
$$P(X|AC) = 7/22\ (0.318)$$
$$P(X|ABC) = 7/19\ (0.368)$$
$$P(X|ABCD) = 6/13\ (0.462)$$
$$P(X|ABCDE) = 6/12\ (0.500)$$

When $A = p24 \geq 2.00''$, $B = p10 \geq 4.00''$, $D = (v - 2.5t \geq 35)$,

$$P(X|A) = 7/17\ (0.412)$$
$$P(X|AC) = 7/16\ (0.438)$$
$$P(X|ABC) = 7/13\ (0.538)$$
$$P(X|ABCD) = 5/9\ (0.555)$$
$$P(X|ABCDE) = 7/13\ (0.538)$$

Finally, when $A = p24 \geq 2.50''$, $B = p10 \geq 4.00''$, $D = (v - 2.5t \geq 35)$,

$$P(X|A) = 4/6\ (0.667)$$
$$P(X|AB) = 4/5\ (0.800)$$
$$P(X|ABC) = 4/5\ (0.800)$$
$$P(X|ABCD) = 4/5\ (0.800)$$
$$P(X|ABCDE) = 4/5\ (0.800)$$
$$P(X|ABCE) = 4/5\ (0.800)$$

Making the assumption of perfect predictability of the set of conditions A, B, C and E, and assuming the existence of condition D, Table 3-5 summarizes the expected loss of precipitation from the seasonal data set, were these avalanche forecasting criteria applied.

3.4.6 Suspension Criteria

Subsequently, with provisions for snow course accumulations incorporated, the following criteria were adopted for the suspension of seeding due to the danger of avalanches along Highway 160 in the Wolf Creek Pass area:

TABLE 3-5

AVALANCHE FREQUENCY BY PRECIPITATION CATEGORY
(U.S. 160 - WOLF CREEK PASS)

	24-HOUR PRECIPITATION IN. (MAXIMUM OF DURANGO, PAGOSA SPRINGS, WOLF CREEK PASS 1E									
Month	0.00	0.01-0.1	0.11-0.25	0.26-0.50	0.51-0.75	0.76-1.00	1.01-1.50	1.51-2.00	2.01-4.00	≥4.00
Nov.	0/279	0 / 28	0 / 18	0 / 23	0 / 12	0 / 7	2 / 15	0 / 3	0 / 1	0 / 0
Dec.	0/253	0 / 33	0 / 28	0 / 30	2 / 21	1 / 15	1 / 5	0 / 6	3 / 10	1 / 1
Jan.	0/245	0 / 37	0 / 30	0 / 30	0 / 14	2 / 14	4 / 13	4 / 4	3 / 6	0 / 0
Feb.	0/224	0 / 35	0 / 32	1 / 25	0 / 14	1 / 7	1 / 4	0 / 0	0 / 1	0 / 0
Mar.	0/246	0 / 37	0 / 45	0 / 38	0 / 9	0 / 9	1 / 10	0 / 6	0 / 1	0 / 0
Apr.	0/247	0 / 36	0 / 39	0 / 33	0 / 18	1 / 9	0 / 6	0 / 1	0 / 1	0 / 0

1) There will be no suspension for avalanche when snowpack is less than 90 percent normal unless the Colorado State Highway Department advises that unusually hazardous snow conditions exist.

2) Snowpack 91 to 120 percent of normal, 24-hour maximum forecast precipitation 2.0 inches or greater water content, and a preceding 10-day accumulation of 4.00 inches or greater water content.

3) Snowpack 121 to 150 percent of normal, 24-hour maximum forecast precipitation, 1.0 inch or greater water content, and preceding 10-day precipitation accumulation of 2.50 inches or greater water content.

4) Snowpack 151 percent of normal or above, 24-hour maximum forecast precipitation of 0.7 inch or greater, and a preceding 10-day precipitation accumulation of 1.75 inches or greater water content. (Note: When snowpack exceeds 200 percent of normal February 1 to February 15, seeding will be suspended due to above-normal snowpack criteria.)

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3. BMD02R – Stepwise Regression Version of June 2, 1964, Health Sciences Computing Facility, University of California at Los Angeles.

CHAPTER 4
LOCAL EFFECTS

It is the purpose of this section to examine several local meteorological effects observed in the project area as they relate to the cloud and precipitation characteristics and the transport and dispersion characteristics over the area.

The following specific phenomena will be examined:

WINDS

1) A southeasterly flow anomaly.
2) Durango upper wind flow.
3) Drainage wind circulations.

TEMPERATURE REGIMES

1) Inversions.
2) Comparison of the Durango upper air temperature data with adjacent NWS stations.

PRECIPITATION CLIMATOLOGY

1) Frequency of precipitation and the expected number of experimental periods per season.
2) The variation in cloud regimes.
3) Cloud top temperature assessment as deduced from the expected cloud regimes.
4) Cloud tops as obtained from Durango radiosonde data.

4.1 WIND AND TEMPERATURE REGIMES

4.1.1 The SE Anomaly

The rawinsonde data obtained during the operating season from the Fort Lewis College site were generally in remarkable agreement with the winds one would have obtained by merely averaging the NWS winds as measured at Grand Junction (GJT) and Albuquerque (ABQ). There was one striking exception. On several occasions when the gradient flow became equal to or more southerly than 220°, a southeasterly current became established up through 700 mb over Durango. Some other pertinent characteristics of this flow include an abrupt veering from southeast to southwest in alignment with the gradient level flow between 11,000 and 14,000 feet M.S.L., which is approximately the height of the main barrier. Also, an inversion, or warming, is usually not evident in the layer exhibiting the maximum veering, as a thermally induced wind shift would require. However, a surface based inversion may or may not exist below this layer. This aberration in the flow has been observed to persist from early morning through evening.

The effect on the project was that several experimental days which otherwise satisfied the experimental day criteria were out-of-spec for varying durations with regard to Durango-measured 700-mb winds. The affected experimental days are those which began on December 14th (1), December 19th (3), February 17th (8), April 14th (23), April 23rd (28) and May 7th (33). All of the above were associated with substantial precipitation, including the heaviest storm (May 7th-8th). Also, of the six experimental days affected, five were "seed" days. Examples of this aberration can be seen by examining the appropriate 700-mb maps in Chapter 6, Experimental Day Data Summaries.

Several explanations or combinations of factors can be advanced to explain this phenomenon. Common ground seems to be found for each of these disturbances in the surface (sea level) pressure distribution and the orientation of the 700-mb flow. In each case, the 700-mb flow was from 220° or less, and the surface pressures were lower toward the southwest and south. From these facts it appears likely that this anomaly is the result of deep boundary (or friction) layer effects which are maximized in southwesterly gradient flow. The surface pressure distribution in these cases combines with frictional effects to result in northeasterly or easterly flow at the surface except when the insolation is significant. In the cases with high insolation, such as April 23rd (28), an Ekman spiral is replaced by southeasterly flow from the surface to 700 mb. This is evidently a compromise flow between the surface pressure gradients and the diurnal mountain valley circulation. A factor in cases of low insolation intensity is the persistent surface based inversion which decouples a shallow layer at the surface upwind of the barrier from the main flow.

Another consideration is localized channeling of the flow up the north-south oriented Animas Valley in which Durango lies. However, pibals taken by WSSI near Edith, Colorado, some 90 km southeast of Durango, substantiate existence of a flow at the southern extremity of the target area. The easterly current does not appear to be as deep over the southeast portion of the target area as was observed in Durango.

Since this anomaly was only observed with an associated passage of a pressure depression or a discrete cyclone center to the south of the project, an attempt was made to ascertain the frequency of such passages. The results of 20 years of cyclone paths for the deep winter (December-March) period are presented in five-year increments in Figures 4-1, 4-2, 4-3, and 4-4.[1] An examination of these charts shows at once that such paths are frequent and may comprise as much as one half of the surface cyclones affecting Colorado during the December-March period. It is also a fact that unless the system passes far to the south, these paths are accompanied by substantial precipitation. For example, this phenomenon was observed on 9 days during the past operating season and all except one were substantial precipitation events, including the five heaviest during that time – December 19-20, January 2-3, February 17-18, February 19-20, and May 7-8. Six of the nine days were experimental days and were affected for various durations or immediately preceded by this anomalous current.

It should also be noted that this regime does not prevail for the entire period of precipitation unless the upper flow also attains a southeasterly orientation, as occurred on February 19-20. The typical sequence at 700 mb was a veering from southeasterly to southwesterly components as the apex of the upper trough neared, usually accompanied by more westerly wind components and decreasing velocities. These latter observations sustain the barrier effect hypothesis. It might also be observed that without local wind measurements taken at Durango and vicinity, this striking phenomenon would have gone undetected. This is so because the readily available wind data at such nearby NWS stations as Grand Junction (GJT), Winslow (INW), and Albuquerque (ABQ) are typically in reasonable gradient flow agreement, as deduced from the 700-mb height field.

Another fact worthy of mention is that the extreme aridity of the past winter season in Arizona and New Mexico was a direct result of the rarity of this type of disturbance. In four out of five seasons likely to be wetter than this past one, this flow anomaly should prove to be common.

The implication of these mesoscale phenomena are fairly obvious. Under the present criteria regarding the orientation of the flow at 700 mb (170°), fairly

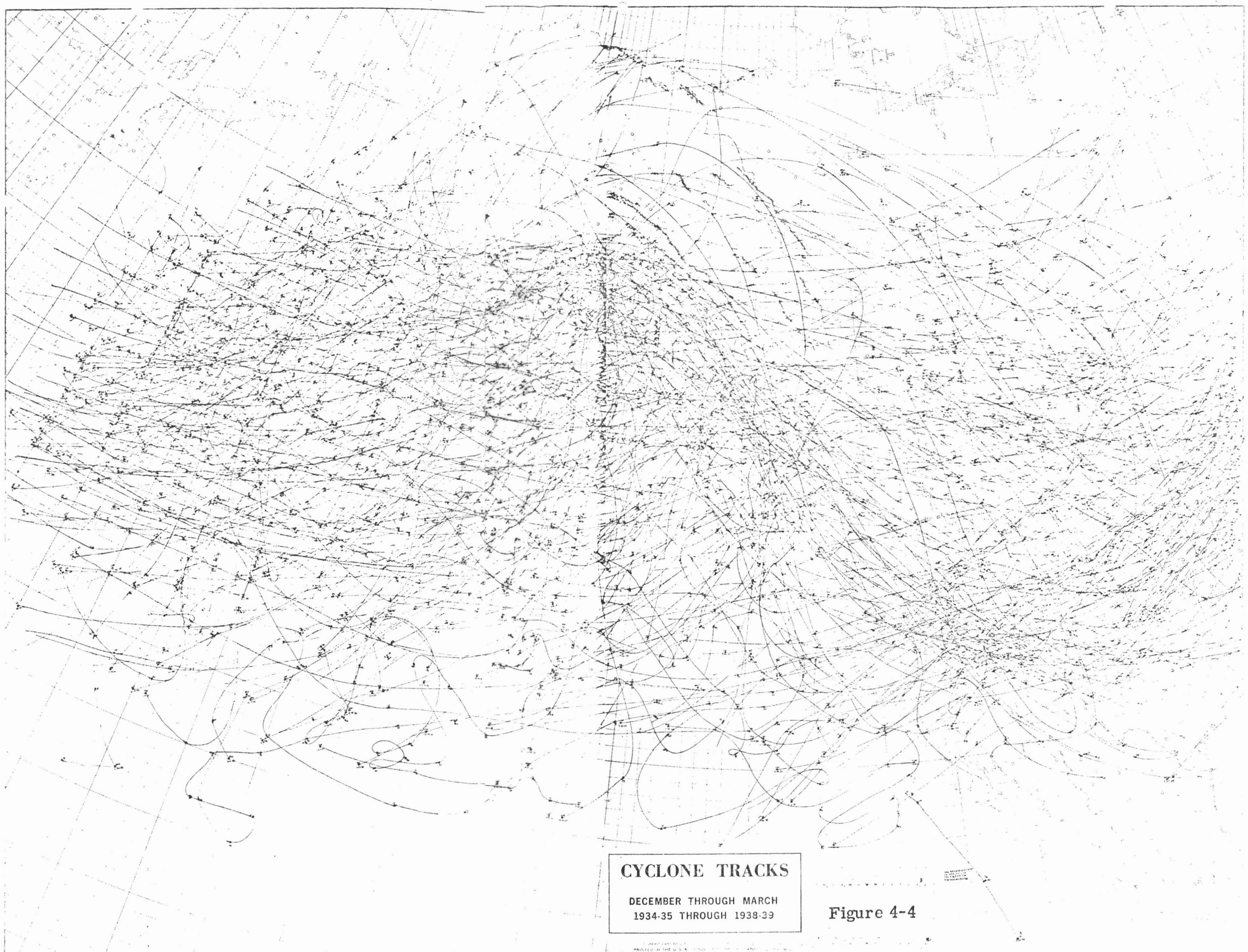
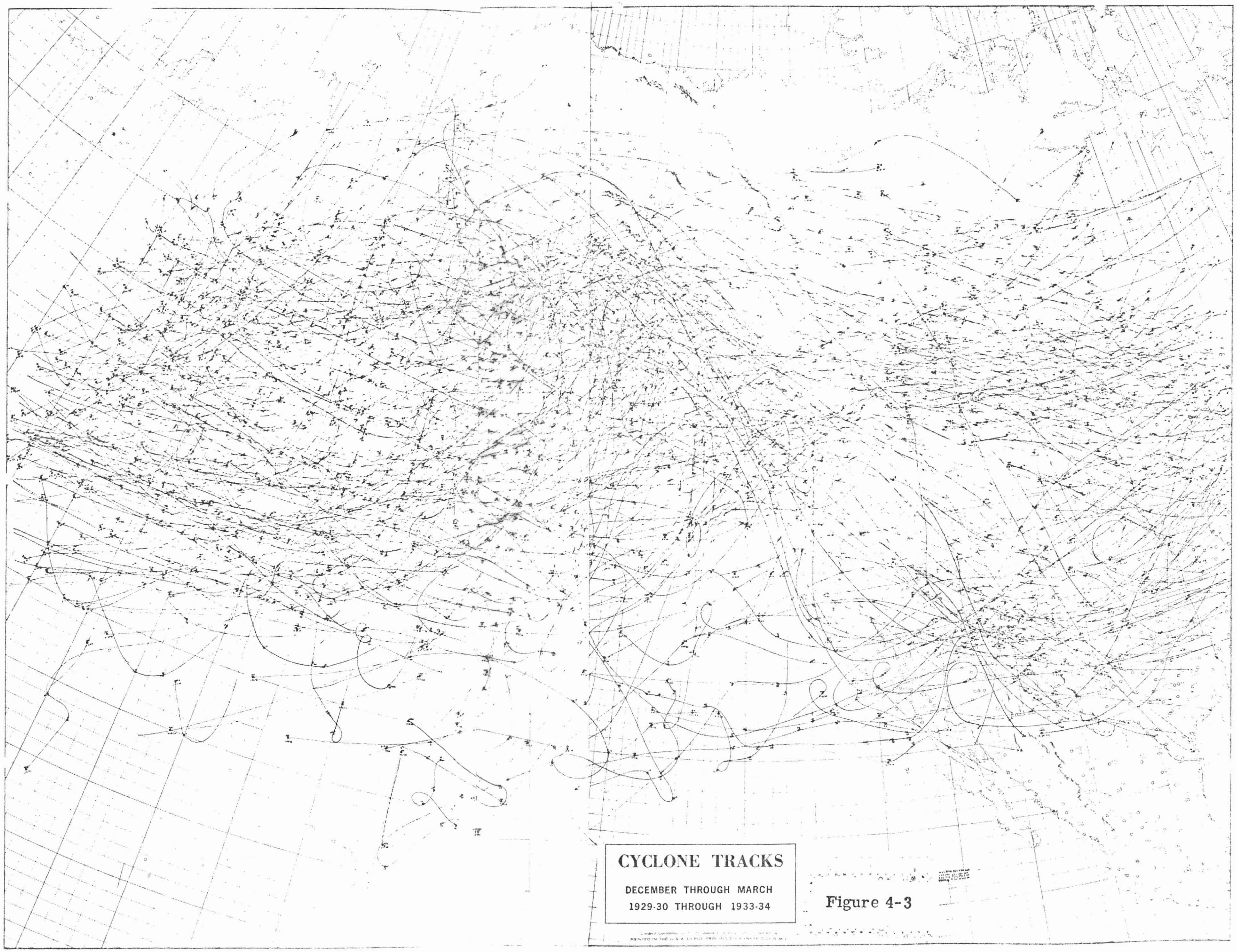

CYCLONE TRACKS
DECEMBER THROUGH MARCH
1934-35 THROUGH 1938-39

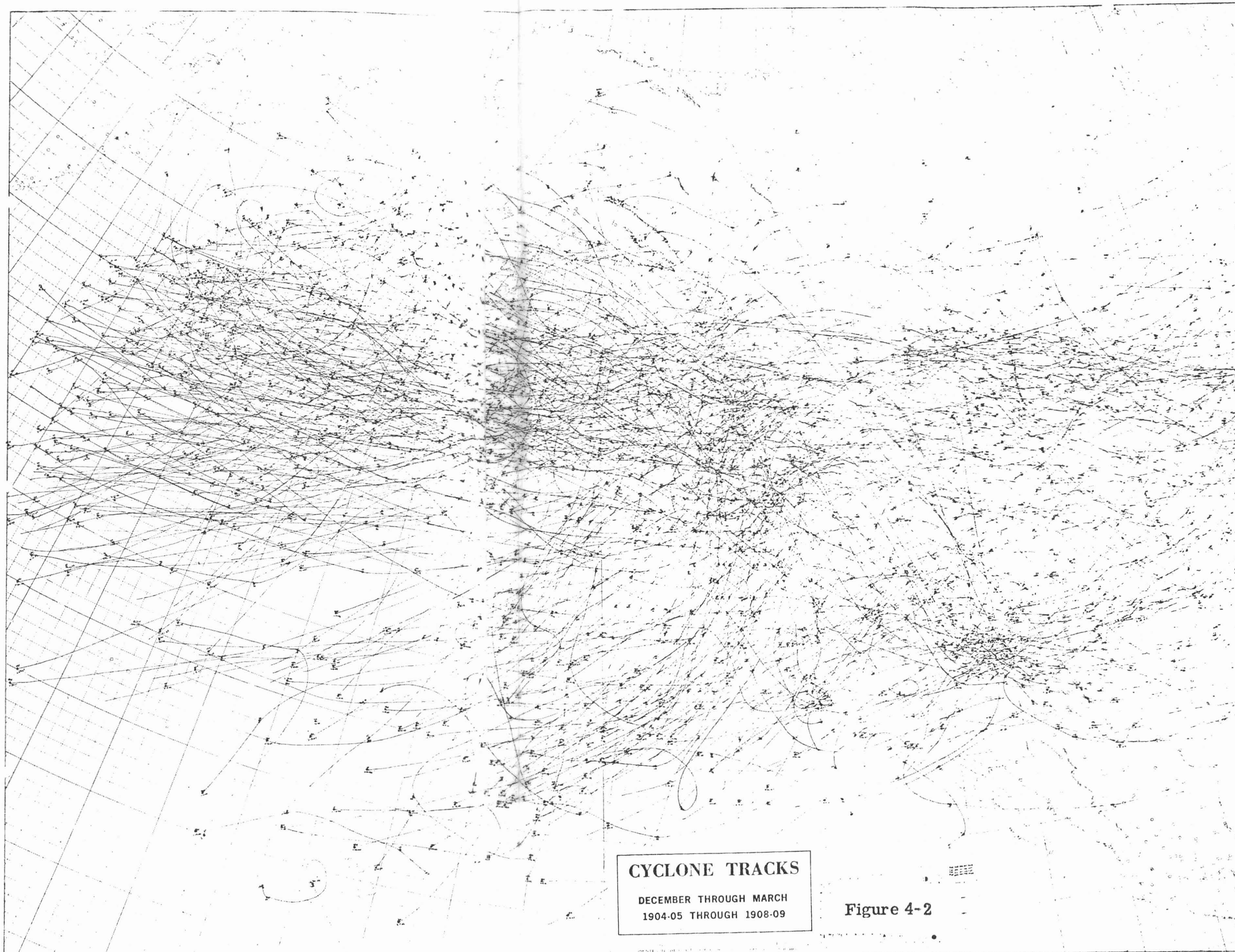
Figure 4-4



CYCLONE TRACKS

DECEMBER THROUGH MARCH
1929-30 THROUGH 1933-34

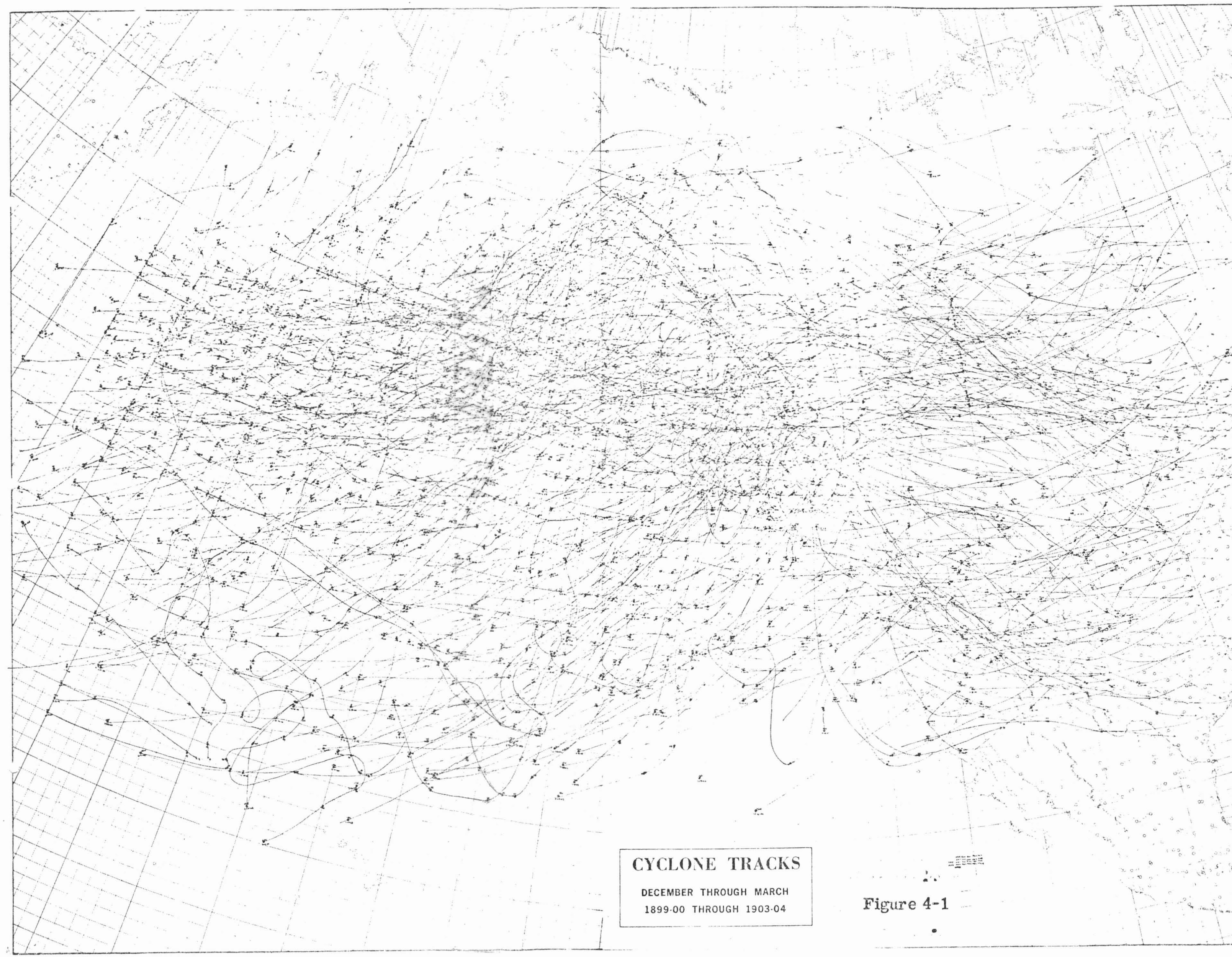
Figure 4-3



CYCLONE TRACKS

DECEMBER THROUGH MARCH
1904-05 THROUGH 1908-09

Figure 4-2



CYCLONE TRACKS

DECEMBER THROUGH MARCH
1899-00 THROUGH 1903-04

Figure 4-1

substantial periods of precipitation may go unseeded as a result of "out-of-spec" winds at 700 mb, as measured by the Durango radiosonde. Also, with southeasterly currents for certain synoptic situations being deeper than expected (currents which are otherwise seedable), "seed" days are likely to have their greatest effect on the more northwesterly portion of the target areas. There were five "seed" days during the past operating season in which this anomaly occurred for various durations. Seeding was conducted during some of these periods due either to an imminent wind shift, or to the fact that initially, when this phenomenon was observed, the Durango rawinsonde observation was suspect since it did not agree with the adjacent NWS stations.

Another suggestion following from this phenomenon is the addition or redeployment of cloud nucleating generators to seed this particular storm type more effectively in the southern portion of the project area. New positions might include the region between Chromo, Colorado, and Chama, New Mexico.

4.1.2 Durango Upper Winds

A characteristic of the winds measured at Durango was a speed that was frequently less than expected (relative to nearby NWS stations) as the radiosonde reached elevations greater than 18,000 feet (Table 4-1). This was believed due to either equipment problems or location of the radiosonde relative to the immediate topography. Accordingly the site has been moved to a point adjacent to Durango Municipal Airport.

TABLE 4-1

DURANGO 500 mb WIND SPEED COMPARISON

	DRO RD-65 Measured	Interpolated ABQ-GJT
All Winds*	31.6 knots	40.6 knots
Interpolated Wind ≥45 knots	43.6 knots	56.8 knots

*Based on 50 observations

4.1.3 Inversion and the Drainage Wind

The Durango (Fort Lewis College) rawinsonde data, the WSSI Edith pibal winds, and the Durango airport surface winds were examined in detail to determine the characteristics of the stability and low-level wind regimes.

The dominant local wind regime during fair weather periods was a mountain-basin diurnal circulation with upslope southerly flow during the daytime, and equally marked downslope drainage wind from the north during the evening through mid-morning. A temperature inversion accompanied the drainage flow. A sampling of 83 non-experimental day 1200Z soundings exhibiting an inversion showed the average depth to be 1850 feet. Extremes ranged from less than 300 feet to more than 7000 feet.

An examination of 83 rawinsondes during the nighttime periods (between 0300Z and 1500Z) of experimental days concurrent with precipitation and 700-mb winds between 150° and 300° reveals that inversion regimes are still significant despite the disturbed state of the weather. Seventy-seven per cent of this experimental day sounding sample still exhibited an inversion even though precipitation was occurring over the target area. The depth of these inversions ranged from less than 200 feet to more than 2000 feet above the site. Of those soundings exhibiting an inversion, 44 (or 69 per cent) were accompanied by light and downslope northerly flow away from the target area in a surface layer.

Corroborating the Durango Fort Lewis site wind regime are the surface wind records obtained from the NWS observation approximately one-half mile north of Durango Municipal Airport. The Durango Airport weather observation for the hours of 0600Z through 1200Z (at two-hour intervals) is taken at this location. A frequency wind rose is presented for this location (Figure 4-5), compiled from observations concurrent with precipitation and with the 700 mb-wind within spec (150-300 degrees). In this case, however, the data are not limited to the experimental day set, but include all those periods meeting the above criteria between 1 November 1970 and 15 May 1971.

Again, as in the case of the Durango-Fort Lewis 7000-foot M. S. L. winds, the dominant flow direction comprises northwest to northeast inclusive. These downslope and away-from-the-target flows comprised 47 per cent of all the wind directions observed during these disturbed situations. The disturbed situations in

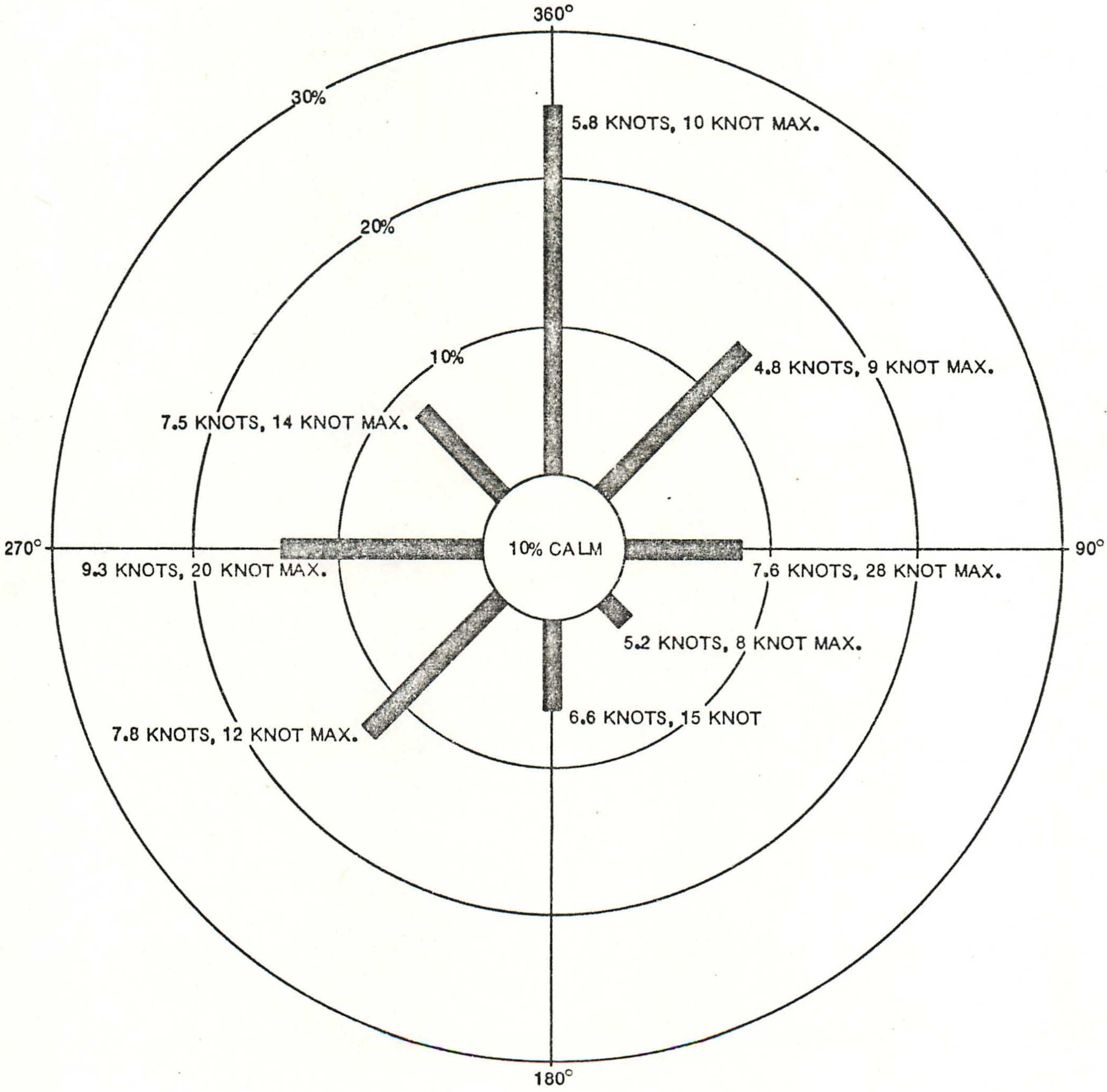


Figure 4-5. Durango Airport Night Surface Winds (2300-0500MST) During Precipitation with 700 mb Wind 150 to 300° (206 Observations, 1 Nov. - 15 May)

which these flows were observed ranged from precipitation only on the high mountain ridges to widespread and heavy precipitation.

At Edith, Colorado, 46 observations during or very near to precipitation periods were evaluated. At the WSSI Edith site, two pibal runs were made per day, low cloud cover permitting. These observations were usually made at 1430-1500Z and again between 2300Z-0000Z. Although the morning sample is limited to 19 observations on experimental days with precipitation, a drainage-like wind is again significant if the drainage source direction is modified to include from 340 to 100 degrees in keeping with the nearby terrain. Ten of nineteen observations (or 53%) fell into this drainage wind category.

During the daytime Durango-Fort Lewis sounding sample (1800-0000Z) inversions were observed on only 4 occasions out of a total of 58 soundings taken concurrent with precipitation episodes. Northerly winds in the surface layer were observed on only 8 soundings in this data sample.

A frequency wind rose compiled from the 8000-foot level winds for all precipitation periods is presented in Figure 4-6 for the Fort Lewis rawinsonde data. Figure 4-7 presents data from the WSSI Edith pibal site at the south end of the target area. Although the gradient wind directions (SSE-WNW) are dominant at this level, the drainage wind directions are still apparent at both locations.

Although this study is based on a small data sample, the results do provide information on the transport and diffusion characteristics over the project target area. It is apparent from these data and the results of Phase I airborne tracer tests that there is significant vertical and horizontal diffusive transport of the seeding material from the seeding sites toward the higher terrain during nearly all the daytime precipitation periods. In some cases this targetting is complicated by the southeast flow anomaly mentioned earlier and by the cases of persisting inversions that do occur.

Based on this data sample, the transport and diffusion conditions during the nighttime periods are not favorable for targetting of cloud nucleating material during a significant portion of the periods of precipitation. The determination of the precise formation mechanism of this drainage direction flow during precipitation conditions will require further study. Because of the disturbed aspects of the meteorological conditions accompanying these so-called drainage winds, they can

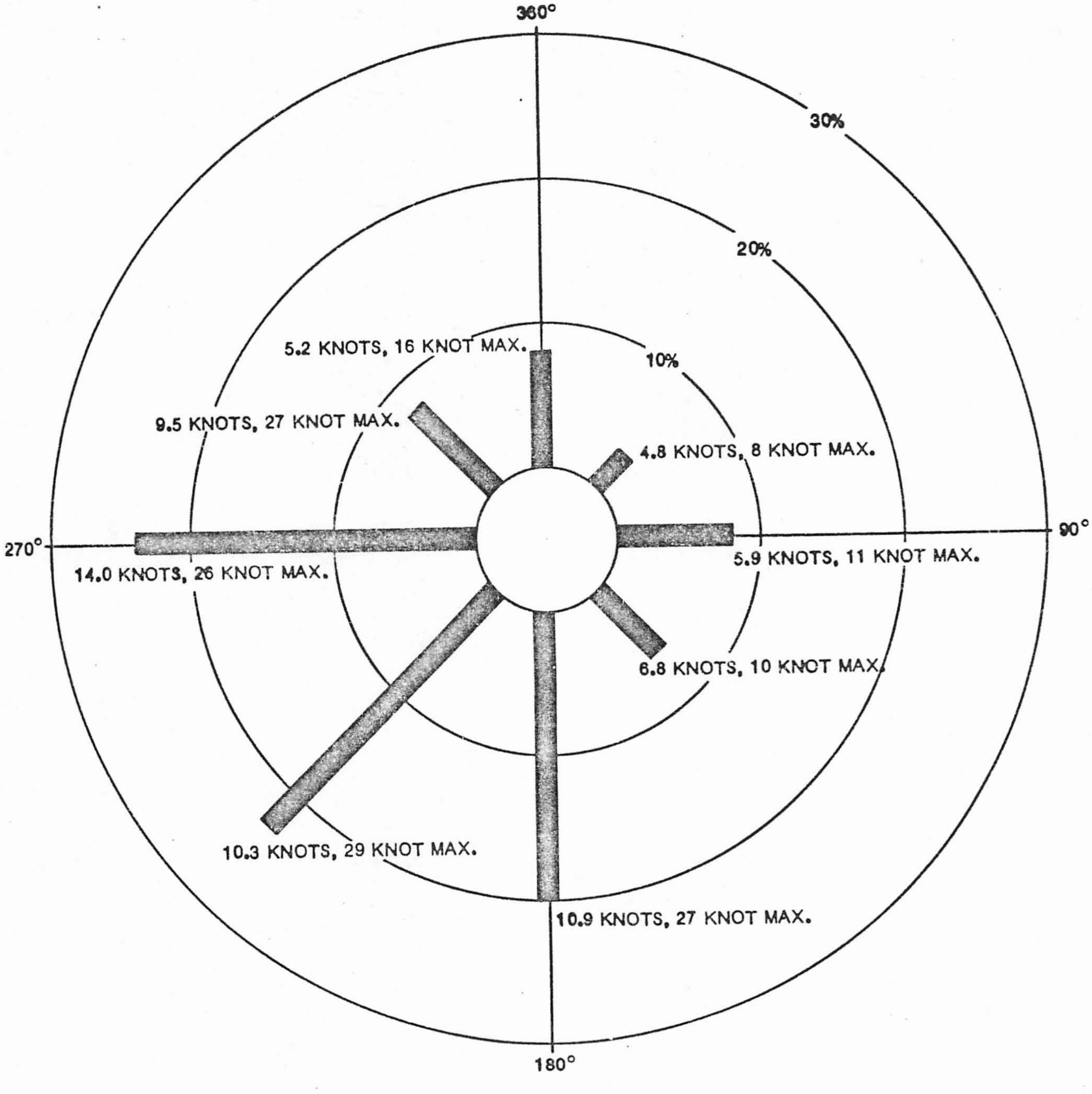


Figure 4-6. Fort Lewis 8000-ft. Rawinsonde Winds During Precipitation Within Experimental Days with 700 mb Wind Between 150 and 300° (152 Observations).

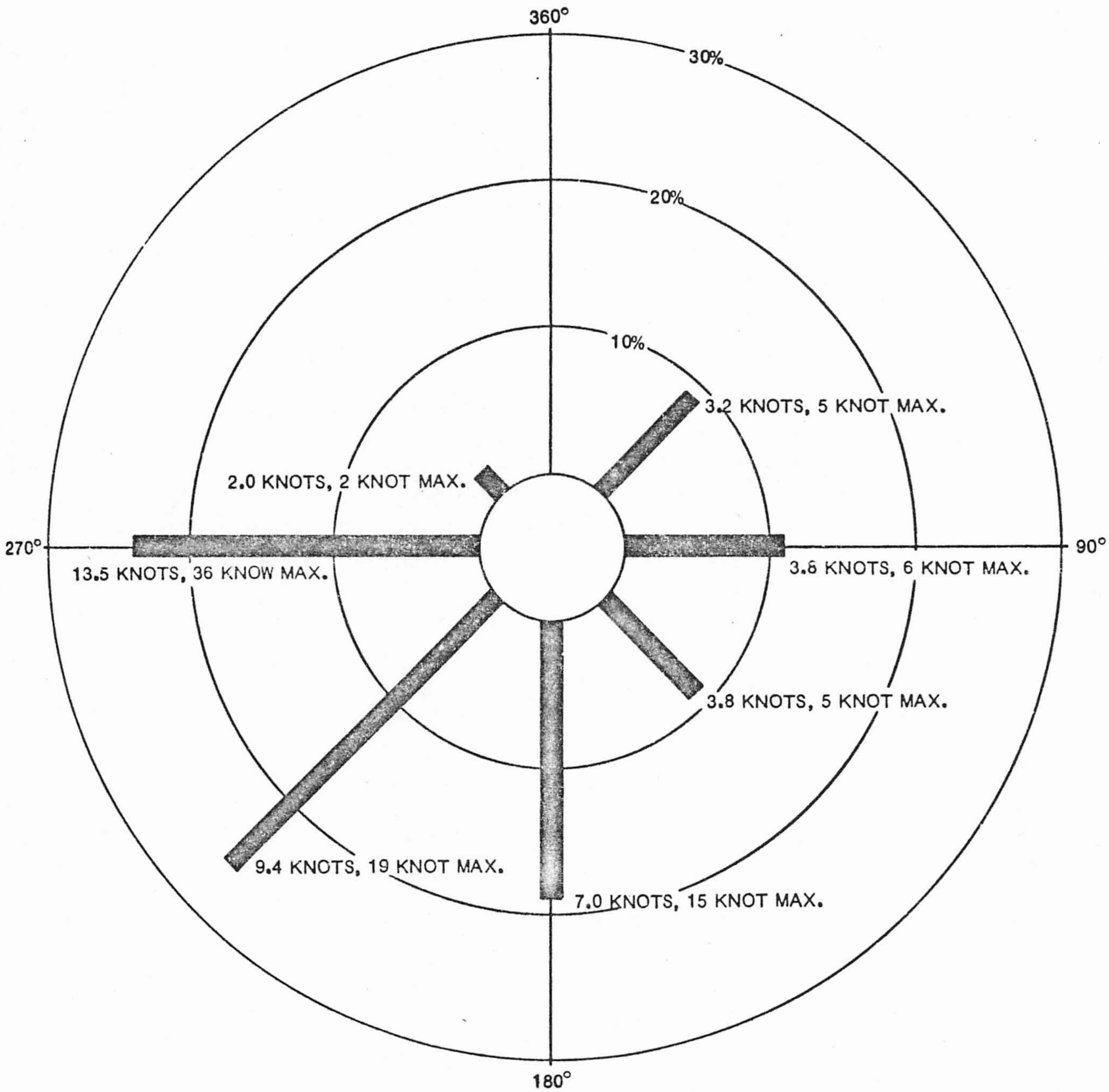


Figure 4-7. WSSI Edith 8000-ft. Pibol Winds Associated With Precipitation on Experimental Days with 700 mb Wind Between 150 and 300° (46 Observations).

not readily be explained by a simple forcing function of a horizontal variation of the potential temperature resulting from the radiational flux. It does appear that the minimal storms with cloud cover restricted to the high terrain and clear skies elsewhere may most nearly approach this condition. In addition there is perhaps a drainage component added by the precipitation in evaporative cooling of the unsaturated layer below the cloud base, and the drag of the precipitation elements themselves. In the larger storms with widespread low cloudiness, the distribution of the surface (sea level) pressure may be more important in reinforcing this drainage direction flow.

This initial study points up the requirement for a detailed analysis of the transport and diffusion conditions from the elevation and location of each individual seeding site during seedable precipitation conditions. The wind flow and temperature structure at individual generator sites should be carefully scrutinized during the succeeding seeding seasons. If effective unseeded periods are included in the seeded sample, they will only dilute the validity of any planned statistical tests of the effectiveness of seeding in producing changes in precipitation.

4.1.4 Comparison of the Durango Upper Air Temperatures to Adjacent NWS Stations

Durango rawinsonde data, with the exception of somewhat less-than-expected 500 mb wind velocities and the 700 mb wind anomaly, showed excellent agreement with expected upper air values obtained by linearly interpolating the desired parameter between NWS stations located at Grand Junction and Albuquerque. Examples may be found in the upper air maps contained in Chapter 6, Experimental Day Data Summaries.

4.2 PRECIPITATION CLIMATOLOGY

4.2.1 The Occurrence of Precipitation

Not too surprisingly, the studies of the expected number of experimental periods during one season based on 0.01 inch falling on one of several climatological stations as opposed to the specified criteria of "0.01 inches anywhere" within the target area have proved to be an underestimate of the number of days actually having precipitation. In this very dry year, 34 experimental days were logged during the abbreviated season beginning December 12, 1970. This includes 11 in March, during which no measurable precipitation fell in Durango.

The above-average number of seedable days is attributable to weak short wave passages accompanied by light precipitation only on the very highest peaks where no measurements are available. It is therefore expected that an average of 50-70 experimental designations will be made in each of the three remaining seasons under the current criteria. It is of interest to note that perhaps as many as 60 would have been made during this past season had it begun on October 15, 1970, as originally scheduled. (This number includes misses during the December 12-May 15 operation season.)

4.2.2 Variation in Cloud Regimes

The tendency of surface cyclone diminution as the cyclones move from the Eastern Pacific ocean to the North American continent during the fall and early winter and the increase in intensity in the spring are directly correlated with a tendency toward certain characteristics of the accompanying cloud regimes. These, too, can be adequately explained by examining the thermal gradients both at the surface and aloft between ocean-continent couplet.

During the late fall and early winter, as the mean jet stream moves steadily southward, the oceanic air masses are increasingly warmer than the continental air masses they are invading (Pyke, 1966). This circumstance favors the accentuation of gradual large-scale ascent of the air mass in the southwesterly onshore flow accompanying cyclones at this time. Subsequently, massive preceding cloud sheets with numerous layers merging and lowering in textbook fashion should predominate the intrusion of oceanic air during this time of the year. The time sections for experimental days 2, 3, and 4, all occurring in December, are particularly illustrative of this pattern. Note the relatively stable lower layers persisting throughout these experimental days as indicated by the potential temperature isotherm spacing.

Conversely, with the rapidly increasing insolation of early spring reversing the land-sea contrast by April (Crutcher and Meserve 1970)[3], even the so-called warm vector of cyclones advancing onshore is frequently colder than the air mass into which it is intruding. Consequently, large-scale upward motion is inhibited. During this past spring, for example, storms were characterized by a pronounced lack of upper preceding clouds and a sudden onset of the precipitating low cloud body. Illustrative of this characteristic are experimental day units number 10 (March 4), 14 (March 13) 24 (April 17), 25 (April 18), 26 (April 20), 28 (April 23), 30 (April 25), 31 (27 April), 32 (May 4), 33 (May 7), and 34 (May 8).

The minimal storms crossing the project area were in general rather sudden in the onset and also brief in the duration of precipitation regardless of the time of year.

4.2.3 Cloud Top Temperature Assessment

Since the experimental day criteria were altered to emphasize predominant cloud top temperatures following April 17th instead of 500-mb temperature as previously used, an exploration of cloud tops, expected and observed, will be discussed.

As noted in the previous section, the cloud sequence for the substantial storminess periods is likely to proceed in two modes.

Mode 1

In the fall and early winter periods the onset of precipitation is preceded by vast cloud systems of laminar clouds merging and lowering. If the seeding is to be fine-tuned to cloud tops alone, this particular mode will pose a limitation on the seeding after the precipitation has been established in the region. This would result from the circumstance (as exhibited in experimental day numbers 2 and 4) that the initial precipitation will emanate from a relatively high-based and high-topped lowering layer of nimbostratus. Seeding would be initiated from one to perhaps as long as several hours after the onset of precipitation on the highest terrain. Continued lowering of cloud top as well as cloud base, as indicated in these examples, will lead to fairly long periods conducive to seeding thereafter. The termination of such a seeding period is likely to depend on the 700-mb wind criteria (300°) unless the upper air temperatures are exceptionally cold in the attendant upper trough.

Mode 2

The second mode, expected to dominate late winter and spring, consists of the "sudden onset" variety characterized by an extremely rapid invasion of low clouds such as stratocumulus, or even cumulonimbus. In this mode, which comprised nearly all of the substantial precipitation periods after March 1st, cloud tops are generally at an acceptable temperature prior to and during the onset of precipitation. However, from the very circumstance which reduces the preceding cloud forms, another obstacle arises: rapidly increasing daytime instability which acts to mushroom the flat-topped stratocumulus clouds of morning into cumulonimbus massifs by mid-afternoon. The cloud temperature criteria thus becomes violated.

The cause of this rapidly increasing instability can be attributed to a number of factors: 1) rapidly increasing isolation intensities during the spring while the upper atmosphere reamins cold (at Grand Junction, March is the coldest month of the year at 500 mb[5]), 2) the rapidly receding area of snow coverage, which thereby reduces the albedo in the region and enhances the insolational effect, 3) the fact that the path of cyclones becomes more northwest to southeast oriented, thus carrying with them anomalously cool air masses which increase the instability effect. This diurnal fluctuation in stability can be observed in the potential temperature time sections for the April and May experimental day.

It is expected from the above that seeding periods will be adjusted to this strong diurnal fluctuation in stability, such as those which occurred on May 4th and May 8th, whereby possible substantial precipitation from cumulonimbi goes unseeded during a "seed" day due to cloud top temperature criteria; however, seeding is initiated during the evening as the project area continues under the influence of the disturbance, and cloud architecture changes from vertical to laminar with acceptably warm tops.

4.2.4 Cloud Tops of the Lowest Layer Using Durango Data

Radiosondes were released on 295 occasions from the Fort Lewis College site. Clouds were detected on 156 of those from the moisture concentration at various levels. On 126, or 30%, of those releases a cloud top was estimated with a confidence level range of from questionable (40-60% confidence) to definite (70-99%). The "definite" category comprised 69% of the total cloud detectable observations. On the remaining 20%, or 30, of the ascents cloud tops were not discernible due to relatively high values of humidity persisting for great elevations.

A statistical sampling of the data for which cloud tops were assigned shows an average of -19.9°C at a pressure of 533 mb, or approximately 17,000 feet MSL for the lowest cloud top. Higher layers were ignored unless there were definite indications of mergings. On experimental days only, cloud tops averaged 20.4°C at 539 mb. Approximately 18% of those soundings indicated the top of the lowest layer to be warmer than -14°C.

Coud tops were estimated in agreement with procedures outlined in Air Weather Service Manual 105-124 (1969)[4].

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3. H. L. Crutcher and J. M. Meserve, 1970: "Selected Level Heights, Temperatures and Dewpoints for the Northern Hemisphere," NAVAIR 50-1C-52. Naval Weather Service Command.

4. "Use of the Skew-T, Log P Diagram in the Analysis and Forecasting," Air Weather Service Manual 105-124, 1969.

5.1 OPERATIONS

5.1.1 Suggested Changes in Operational Criteria

The operational criteria should be modified slightly so that no significant seeding opportunities are missed and so that effort is not expended on extremely low-potential periods. As the criteria now stand, the precipitation criterion of 0.01 inch anywhere in the target area is not compatible with the requirement of 12-hour duration of correct wind and 500-mb temperature conditions.

Change criteria with respect to the acceptable duration of wind and cloud tops, now required to be 12 hours, to be more compatible with the specification of the precipitation event, 0.01 inch. Criteria deteriorate for sudden onset storms of less than 12-hour durations; the reasons for this are: 1) 0.01 in. may fall in a period of less than 10 minutes rather frequently during the operating season, and 2) as an analysis of the spring storms has indicated, there may be no clouds over the project area from which to determine the onset of precipitation — the major storm of Experimental Day 14 is an example of this. Also, under existing stipulations, significant seedable precipitation conditions often become arbitrarily voided by the wind and temperature 12-hour duration criteria. For example, six hours of significant precipitation can be missed because of a wind shift at the end of that period, while, in other cases, even a few minutes of precipitation can qualify.

It is therefore recommended that the operating criteria be modified to one of the following:

1) An experimental period shall be defined as one in which the experimental criteria are met at any time during the 24-hour unit of designation.
2) A minimum of 3 hours of meteorological conditions simultaneously satisfying the operating criteria is required for the designation of the 24-hour unit as an experimental day.
3) A minimum of 6 hours of meteorological conditions satisfying the operating criteria is required for the designation of the 24-hour unit as an experimental day.

The net effect of these changes would be to increase the number of experimental periods accrued during the season. During the past season from 15 October to 15 May no precipitation event was of less duration than between 2 and 3 hours.

The precipitation criterion of 0.01 in. anywhere in the project area should be liberalized as follows:

1) Change the precipitation event criteria to read $\geq$ 0.03 in. at a project gage rather than 0.01 in. anywhere in the project area. Because it was felt by the forecaster on several occasions that precipitation of 0.01 in. was destined to occur on only the highest, craggiest peaks and was not likely to be recorded in a project gage, the effect would be to minimize insignificant precipitation events.
2) Add a criterion to include the degree of coverage of a seedable cloud layer. Broken or greater coverages on the Divide (0.6 - 1.0 sky coverage) would be sufficient for an experimental day. Scattered cloudiness (0.0 to 0.5 coverage) would not meet this experimental criterion. The effect would be to make the selection of precipitation events on experimental days more realistic.

In the light of wind effects observed over the target area, the flow criterion should be modified to be based on a measured composite flow picture over the entire area rather than the geostrophic flow at 700-mb or the local sounding 700-mb flow. The following observations should be included in this modified composite flow criterion.

1) Measured flow at 8000 through 12,000 ft at Grand Junction and Albuquerque.
2) Measured flow from the surface through 12,000 ft at Durango Airport and Edith.
3) Surface wind measurements from selected generator sites.

Some provision might also be made to eliminate from consideration minimal storms with strong persistent drainage inversions.

In the interests of efficiency, provision should be made for the declaration of an experimental day at, say, 9:00 PM as well as 9:00 AM. In cases where a precipitation period is expected to begin, for example, at 0900 the next morning, the randomization decisions and official declaration should be delayed until at least the evening forecast time.

5.1.2 Suggested Changes in Meteorological Support

The time-share cross sections should be based on trajectory calculations and on the NMC grid point data so that true up-trajectory cross sections are available.

A generator selection model should be programmed in the time-share computer and the initial selection of generators updated frequently based on local data inputs. It is suggested that the outer (40-45 mile) generator line be used more liberably and that turn-on lead times be increased so that control is completely flexible at the discretion of the Project Forecaster.

5.2 INSTRUMENTATION

The following changes in project instrumentation are recommended based on the first season's operational experience:

1) Wind direction and speed, properly averaged, should be telemetered from all remote generator sites and recorded at selected manual generator sites.
2) A tracking radar of rawin unit should be located SSW of Pagosa Springs, and complete accurate wind profiles should be obtained at a maximum of 3-hour intervals.
3) If the seeding system operation is indeed to be based on cloud top temperature, this should be measured with a vertical pointing 1 cm radar, lidar, or other suitable cloud top measuring system.
4) Additional airborne ice nuclei counting should be done in the area to verify diffusion model predictions; also the ice crystal/ice nuclei ratio should be measured routinely in the project area.
5) Mountain top weather stations should be relocated to less severe environments until proven sensors are developed and tested.
6) An improved tracking device should be made available for rawin tracking from the Durango airport.

7) Temperature profiles should be obtained on the southeast end of the network from an additional sonde or temperature profile system.

8) Radar PPI and vertical profiles should be available within the target area on all experimental days. Chaff release rockets should be used for wind tracking during selected periods.

9) An APT satellite readout should be made available in the Durango Forecast Center.

10) A photographic procedure should be established such that a minimum of one infrared photograph is taken during the darkness portion of experimental days, toward the target area from the relocated rawinsonde site adjacent to the Durango airport. Photographic requirements may be upgraded at the discretion of the Project Manager or Forecaster.

5.3 GENERATOR AND GENERATOR NETWORK

The following modifications should be made to the present generator networks:

1) At least one generator should be located southeast of the target area towards Chromo for targetting during southeasterly flow.

2) If, indeed, it is desired to target Area 1 during 250° - 300° flow, a line of high generators should be established to the north of Durango.

3) The No. 11 generator site should be relocated 2 miles to the west.

CHAPTER 6
EXPERIMENTAL DAY DATA SUMMARIES

The data summaries presented in the ensuing pages will continue into Volumes 2 through 7. These data are presented by groups which contain one or more experimental days. This method of presentation was chosen because supplementary upper air and surface meteorological analyses were taken before, between, and after the actual experimental days. Presentation by group therefore makes it possible to provide desirable continuity while avoiding repetition of this supplementary material

The complete data set consists of fourteen groups, as delineated in the following table.

TABLE 6-1. DATA GROUP ORGANIZATION

Group	Experimental Day	Date
1	1	14 December 1970
2	2	17 December 1970
	3	19 December 1970
	4	20 December 1970
3	5	27 December 1970
4	6	2 February 1971
5	7	15 February 1971
	8	17 February 1971
6	9	22 February 1971
7	10	4 March 1971
8	11	8 March 1971
	12	10 March 1971
	13	11 March 1971
	14	13 March 1971
	15	14 March 1971
	16	16 March 1971
	17	17 March 1971
9	18	23 March 1971
	19	25 March 1971
	20	26 March 1971
10	21	7 April 1971
	22	8 April 1971
11	23	14 April 1971
12	24	17 April 1971
	25	18 April 1971
	26	20 April 1971
	27	21 April 1971
	28	23 April 1971
	29	24 April 1971
	30	25 April 1971
	31	26 April 1971
13	32	4 May 1971
14	33	7 May 1971
	34	8 May 1971

Within each of the fourteen data groups the following data units are presented:

- Meteorological Summary of Each Experimental Day

These summaries discuss the salient meteorological features existing over the project area during each of the 34 experimental days of the 1970-71 season. Particular attention is paid to cloud structure changes and how they affect the precipitation modification potential over the target area.

- Upper Air Maps

The 500-mb and 700-mb analyses produced by the Project Forecaster in the Project Meteorological Center are presented here. Supplemental analyses precede and follow each experimental day, thus providing meteorological continuity. For each synoptic time a 500-mb chart is presented, followed by a 700-mb chart.

- Surface Maps

The National Meteorological Center surface analyses for the synoptic times of 0000Z and 1200Z are reproduced for the experimental days.

- Satellite Photos

Selected photos taken on experimental days from the NOAA and ITOS satellites are reproduced.

- Local Rawinsonde Atmospheric Soundings

The local soundings released from the Fort Lewis College site at nominally three-hour intervals on experimental days are plotted on pseudo-adiabatic thermodynamic diagrams. All contact data tabulations and reduced wind data are presented for the soundings plotted here as well as the daily 1200Z ascents in the Appendix.

- Time Sections

Four time sections for each experimental day are presented. The vertical profiles of dry bulb temperature, relative humidity, dry bulb potential temperature, and wet bulb temperature have been computed for each of the local rawinsonde ascents, compiled in a time section format, and analyzed.

- Atmospheric Cross Sections

Atmospheric cross sections of four parameters for the synoptic times of 0000Z and 1200Z are presented. The vertical profiles of relative humidity, potential temperature, wet bulb potential temperature and moist potential temperature were computed for upper air sounding stations along the streamline through the project area, organized into a cross section format, and analyzed in the Project Meteorological Center.

- Diffusion and Transport Analyses

For each seeded experimental day, a diffusion and transport analysis is presented for the generators operating at 0000Z and 1200Z. The transport direction of the plume axis from each generator is indicated. The wind directions selected for determining plume transport were a subjective mean of the winds from the surface through twelve thousand feet measured at Fort Lewis and Edith. Surface winds from the generator site meteorological stations were used for guidance where available. Where there was a definite lower layer of differing flow direction and speed, the following simple model was applied. The plume axis was assumed to rise at 0.5 $msec^{-1}$, and the residence time in the layer was calculated. The trajectory was then calculated using the wind speed in the layer and the plume axis, which was assumed to turn abruptly in alignment with the flow direction in the layer above.

Also, on each of the diffusion and transport figures the concentration predictions of the Pasquill-Gifford dispersion model are indicated. The plume centerline concentrations in nuclei $liter^{-1}$ are indicated along the plume axis, and the ± three standard deviation plume widths from the axis are indicated as the plume edges. The concentrations on the edges of the plume indicated are 0.011 of the plotted centerline values. The following assumptions and parameters were utilized in the diffusion calculations:

Source Strength

Effectiveness at -15°C = 7.0×10^{14} nuclei gm^{-1}
(chosen half way between maximum flow calibration curve and natural draft curve on semi-log plot, Figure 6-1)

$$Q = 3.89 \times 10^{12} \text{ nuclei sec}^{-1}$$

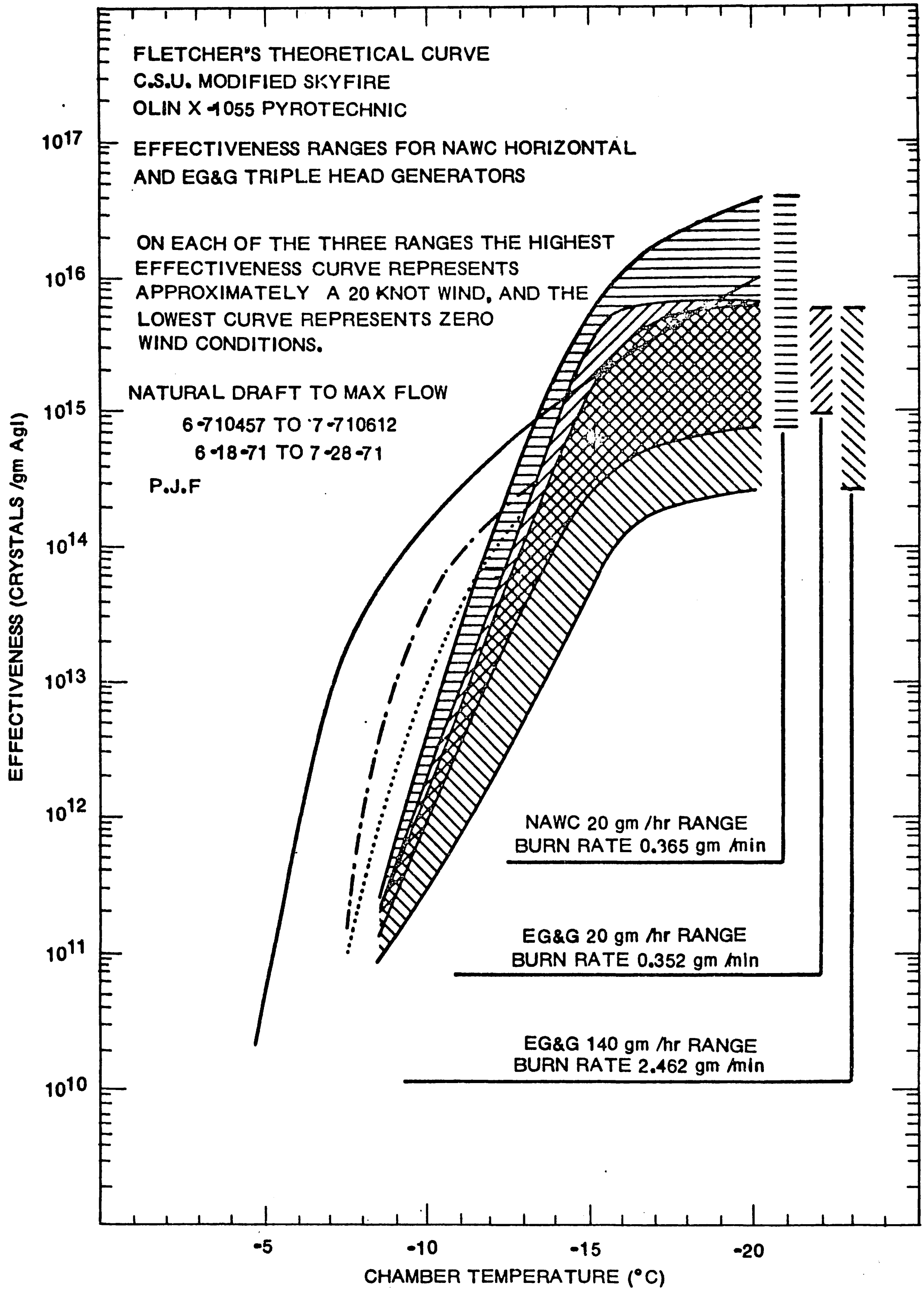


Figure 6-1. C. S. U. Composite Effectiveness Calibration Curves for Project Generators

Plume Centerline Concentration

$$\chi = (x, y, z, H) = \frac{Q}{2\pi \ \sigma y \ \sigma z \ u}$$

Category D or Neutral Conditions were assumed, and the parameters of Table 6-2 were used in the diffusion calculations presented in subsequent data tabulations.

TABLE 6-2. DIFFUSION MODEL PARAMETERS

$\frac{d}{km}$	Category D Stability σ_y (m)	σ_z (m)	$\sigma y \ \sigma z$	χu $\frac{\text{nuclei-m}}{m^3 \text{ sec}}$
5	300	88	2.64×10^4	23.4×10^6
10	550	136	7.49×10^4	8.28×10^6
15	785	171	1.34×10^5	4.62×10^6
20	1000	200	2.00×10^5	3.10×10^6
25	1210	231	2.795×10^5	2.22×10^6
30	1420	253	3.59×10^5	1.727×10^6
40	1820	295	5.38×10^5	1.151×10^6
50	2200	329	7.24×10^5	0.856×10^6

- Nuclei Count Data

Four ice nuclei counters were operated in the project area as follows:

Mesa Verde Park Headquarters - Bigg-Warner Expansion Counter
Red Mountain Pass, Idarado Mine - Bigg-Warner Expansion Counter
Vallecito Reservoir - NCAR Acoustical Counter
Wolf Creek 1E - NCAR Acoustical Counter
(This counter was moved 11 miles NE on 23 March 71 to a location near South Fork, Colorado.)

The data from these four counters are tabulated and plotted in a single figure for each experimental day whenever available. The acoustical counters were operated at -20°C.

- Additional Data

For selected days, outputs of the EG&G numerical precipitation model are presented. Radar data are also included when available.

EXPERIMENTAL DAY 1

(14 Dec 70 - 15 Dec 70)

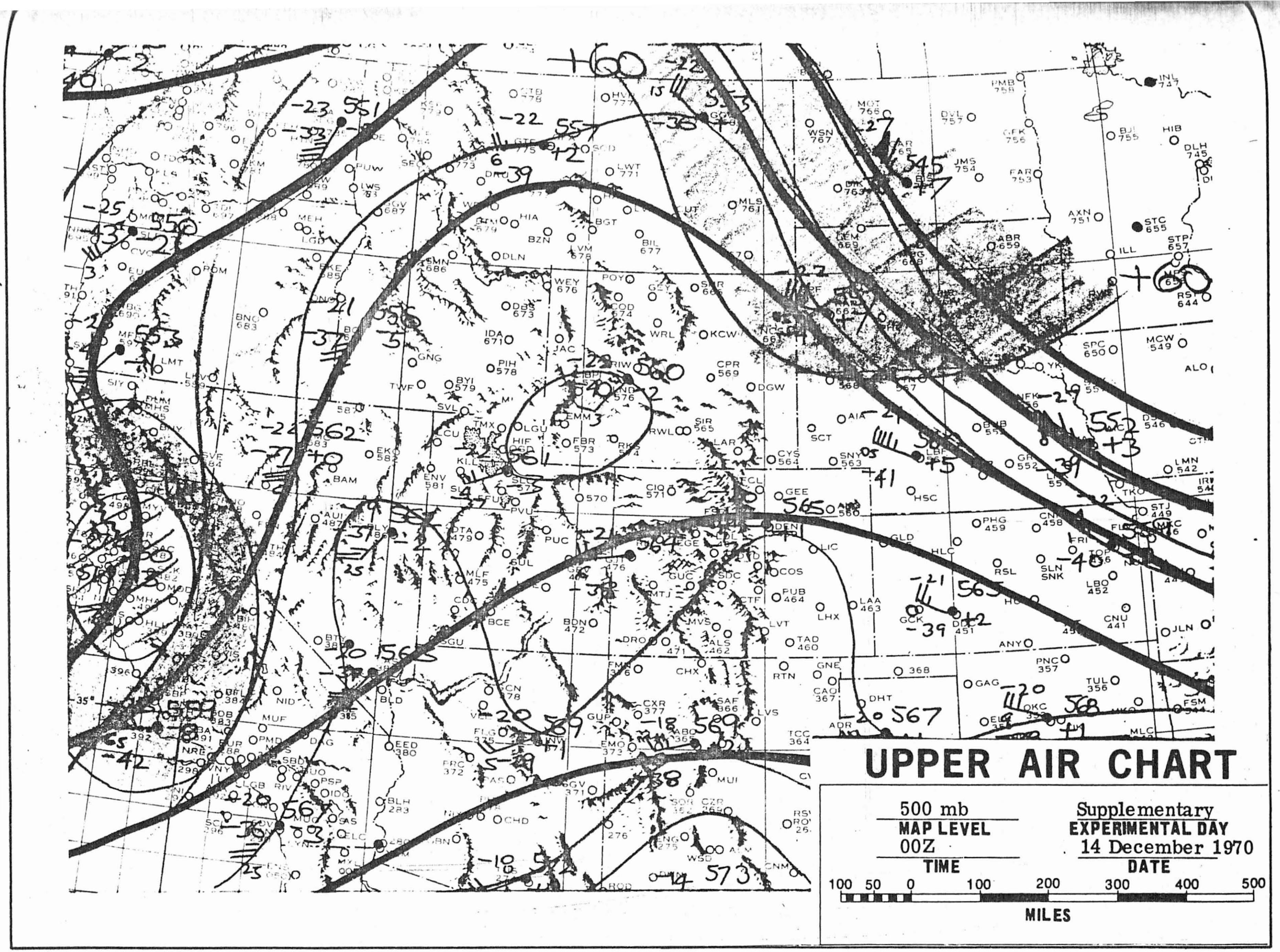
"DO NOT SEED"

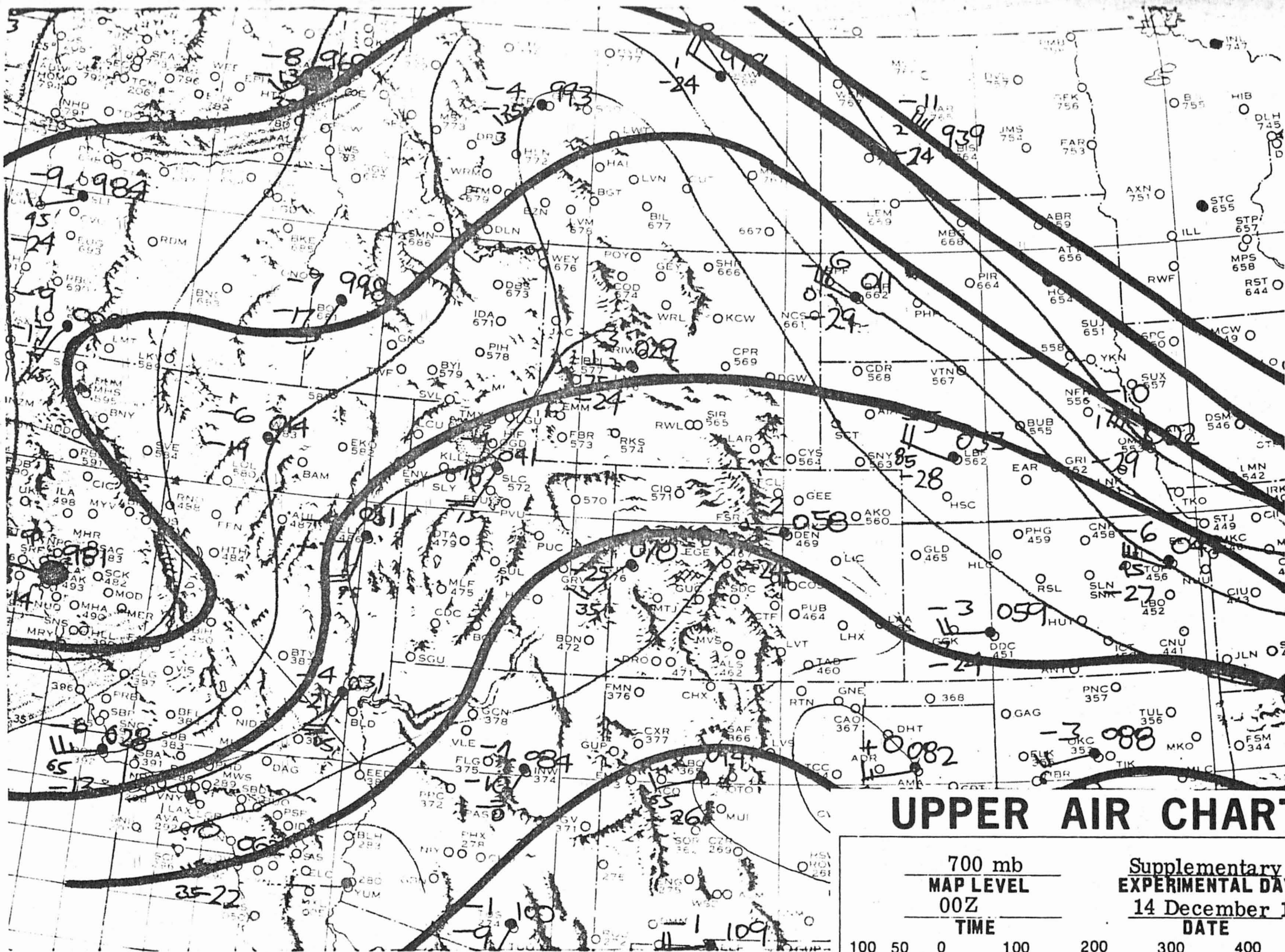
During the night of December 13-14th, a strong 500-mb trough moved south-southeastward from the coast of northern California to the interior of southern California by 1200Z on the morning of the 14th. Strong and increasingly more moist south-southwesterly flow developed over the pilot project area during the day of the 14th. Precipitation was observed to begin in the project area between 0100 and 0200Z, and continued through the end of the experimental day. Trough passage occurred near midnight.

As the core of the upper trough approached during the evening of the 14th, a gradual decrease in upper winds was observed, coinciding with a veering from approximately due southerly at 1910Z to west-northwesterly by 1200Z of the following morning.

On the surface, a weak low pressure area formed over southern Nevada and moved east-southeastward across northern Arizona and New Mexico. Rapid intensification occurred as it approached the Texas Panhandle.

Concommitantly with trough passage, the 500-mb temperature decreased steadily from near -21°C at 1910Z to near -28°C by 1200Z of the following morning. Cloud tops were estimated from the radiosonde data to be at -16°C (16,000 ft) at 0415Z and at -15°C at the top of a lowest layer at 1200Z on the 15th. Due to malfunctions, no other radiosonde data pertinent to cloud tops during the period of precipitation are available.


UPPER AIR CHART
500 mb
MAP LEVEL
00Z
TIME
Supplementary
EXPERIMENTAL DAY
14 December 1970
DATE
100 50 0 100 200 300 400 500
MILES



UPPER AIR CHART

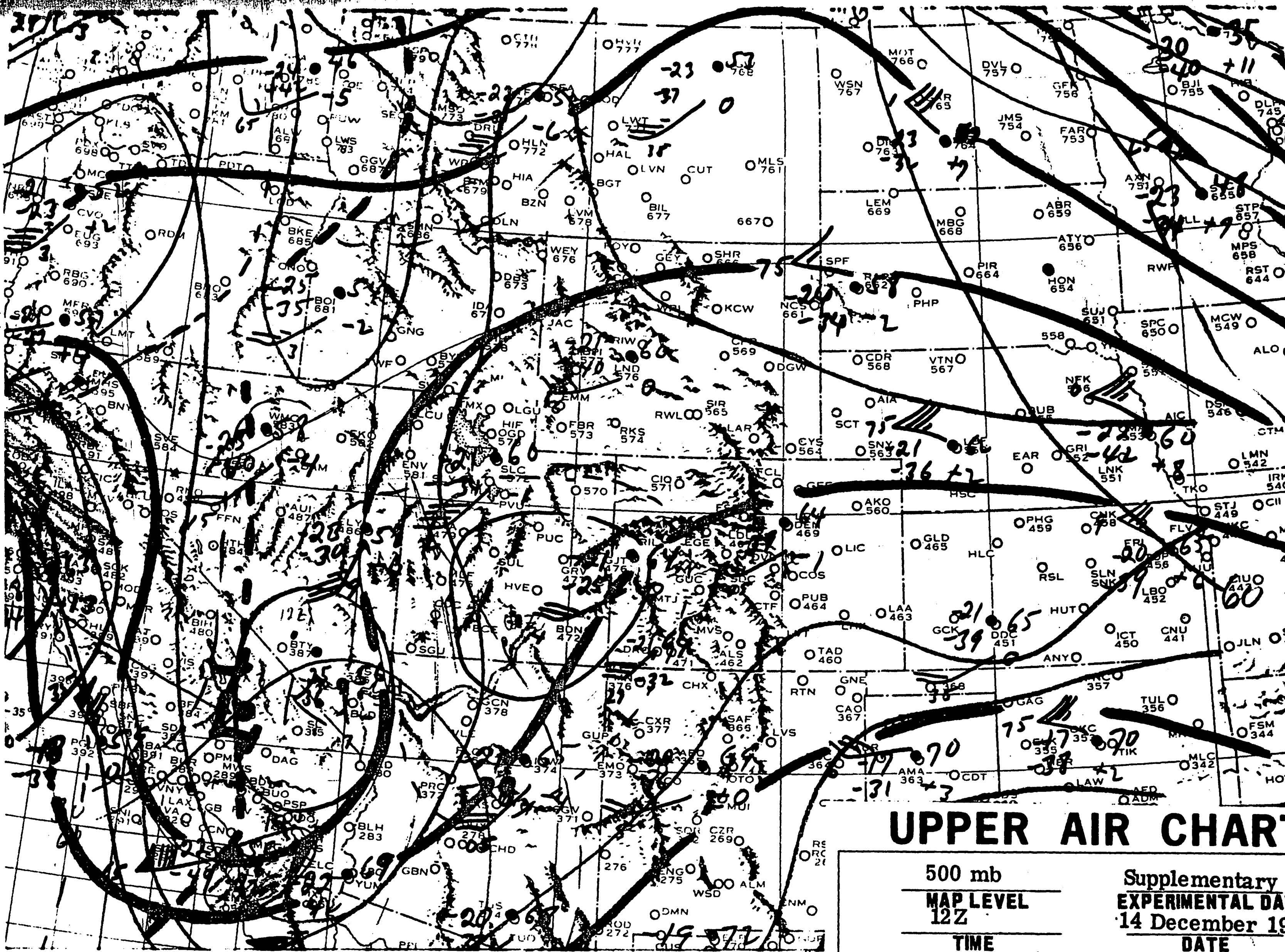
700 mb
MAP LEVEL

00Z
TIME

Supplementary
EXPERIMENTAL DAY

14 December 1970
DATE

100 50 0 100 200 300 400 500
MILES

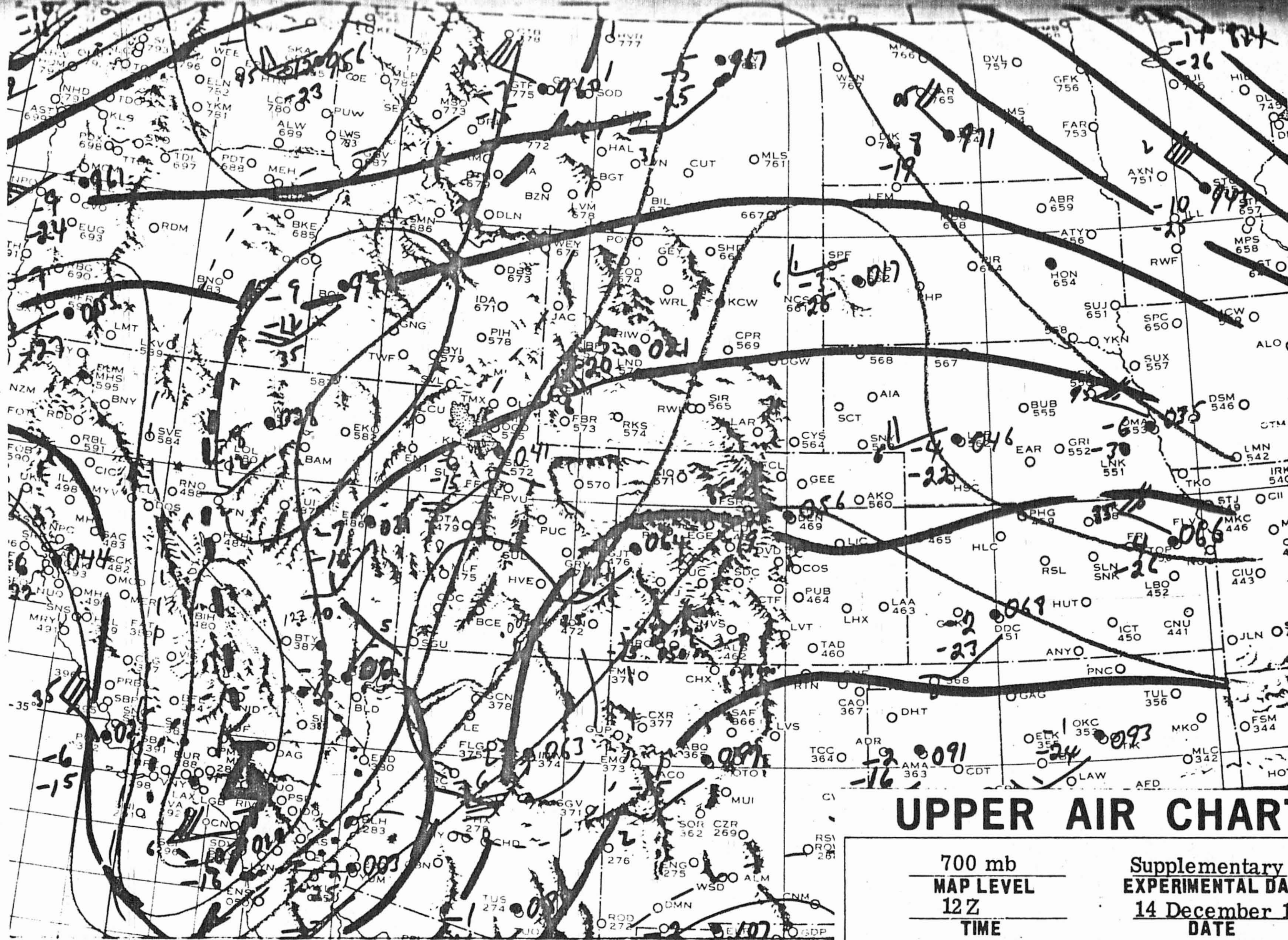


UPPER AIR CHART

500 mb
MAP LEVEL
12Z
TIME

Supplementary
EXPERIMENTAL DAY
14 December 1970
DATE

160 50 0 100 200 300 400 500
MILES

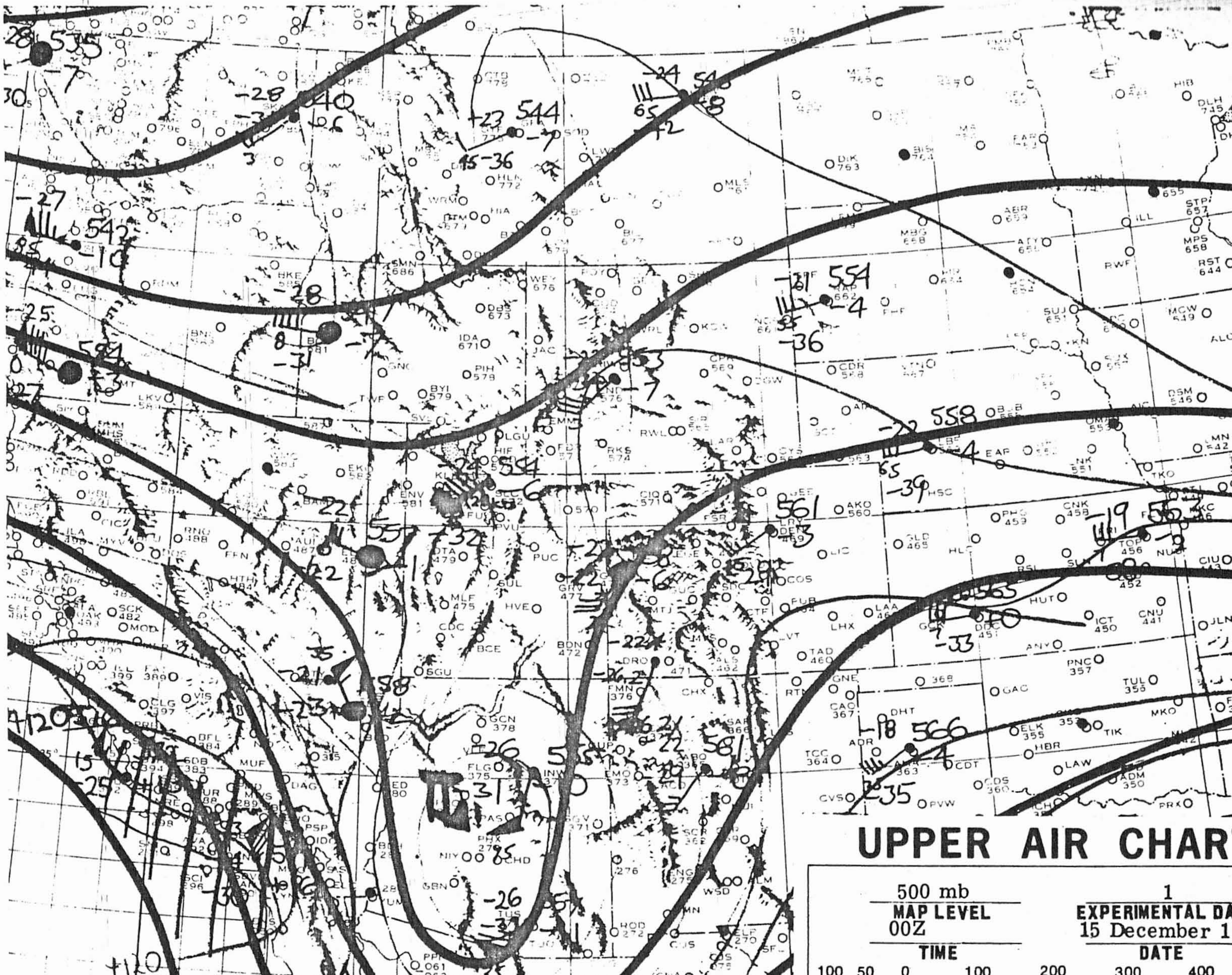


UPPER AIR CHART

700 mb	Supplementary
MAP LEVEL	EXPERIMENTAL DAY
12Z	14 December 1970
TIME	DATE

100 50 0 100 200 300 400 500

MILES

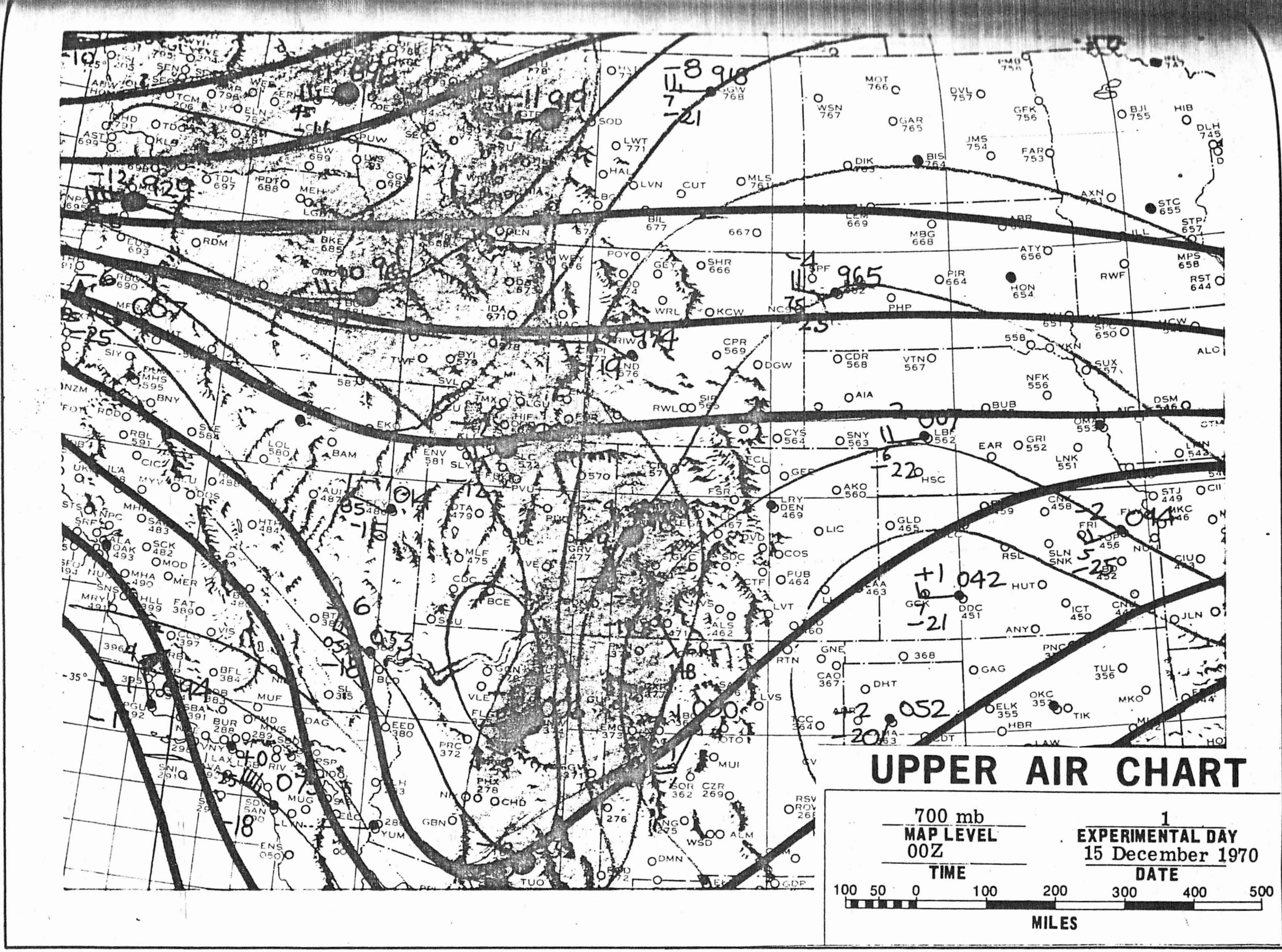


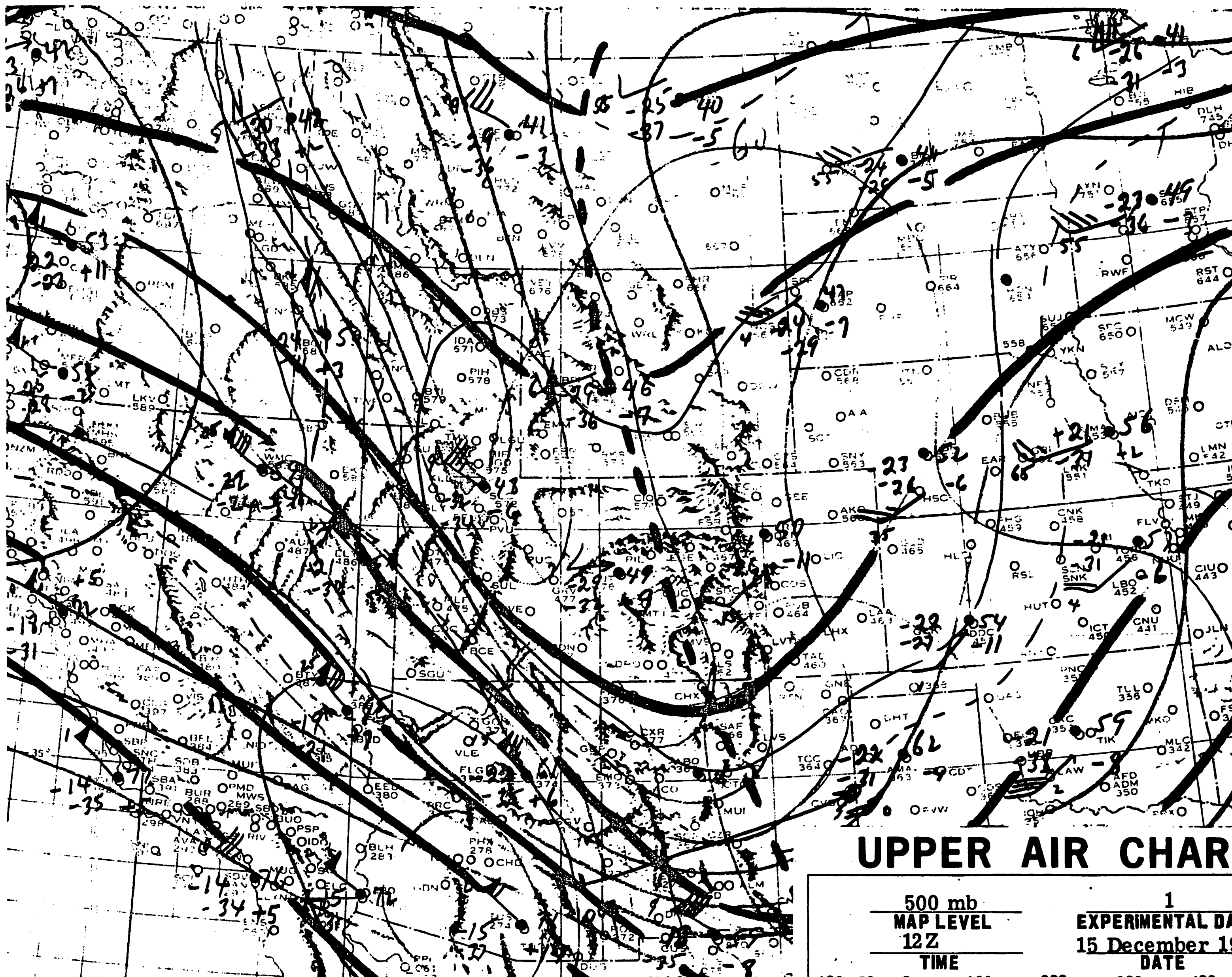
UPPER AIR CHART

500 mb	1
MAP LEVEL	**EXPERIMENTAL DAY**
00Z	15 December 1970
TIME	**DATE**

100 50 0 100 200 300 400 500

MILES


UPPER AIR CHART
700 mb
MAP LEVEL
00Z
TIME
1
EXPERIMENTAL DAY
15 December 1970
DATE
100 50 0 100 200 300 400 500
MILES

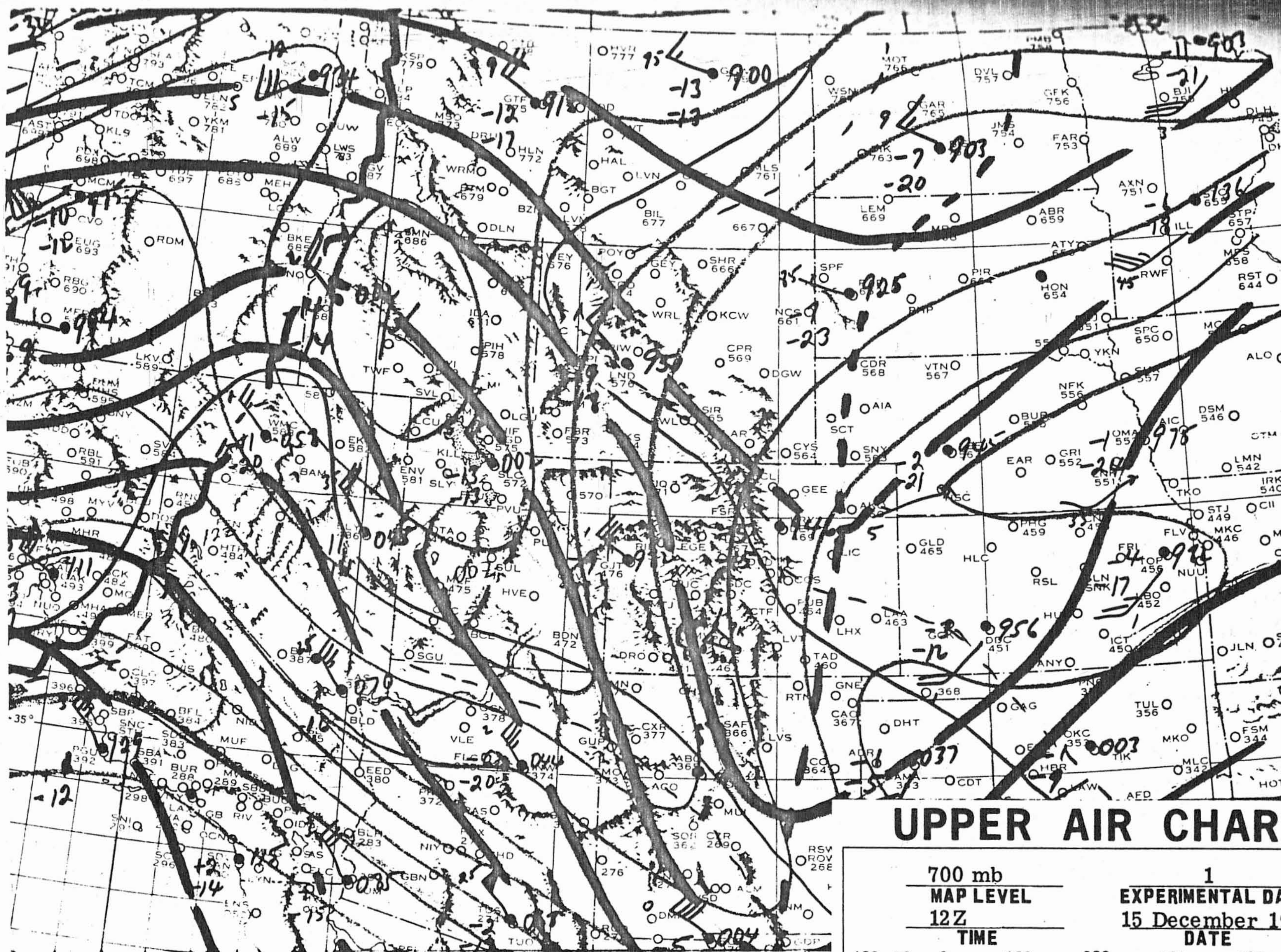


UPPER AIR CHART

500 mb	1
MAP LEVEL	**EXPERIMENTAL DAY**
12Z	15 December 1970
TIME	**DATE**

100 50 0 100 200 300 400 500

MILES

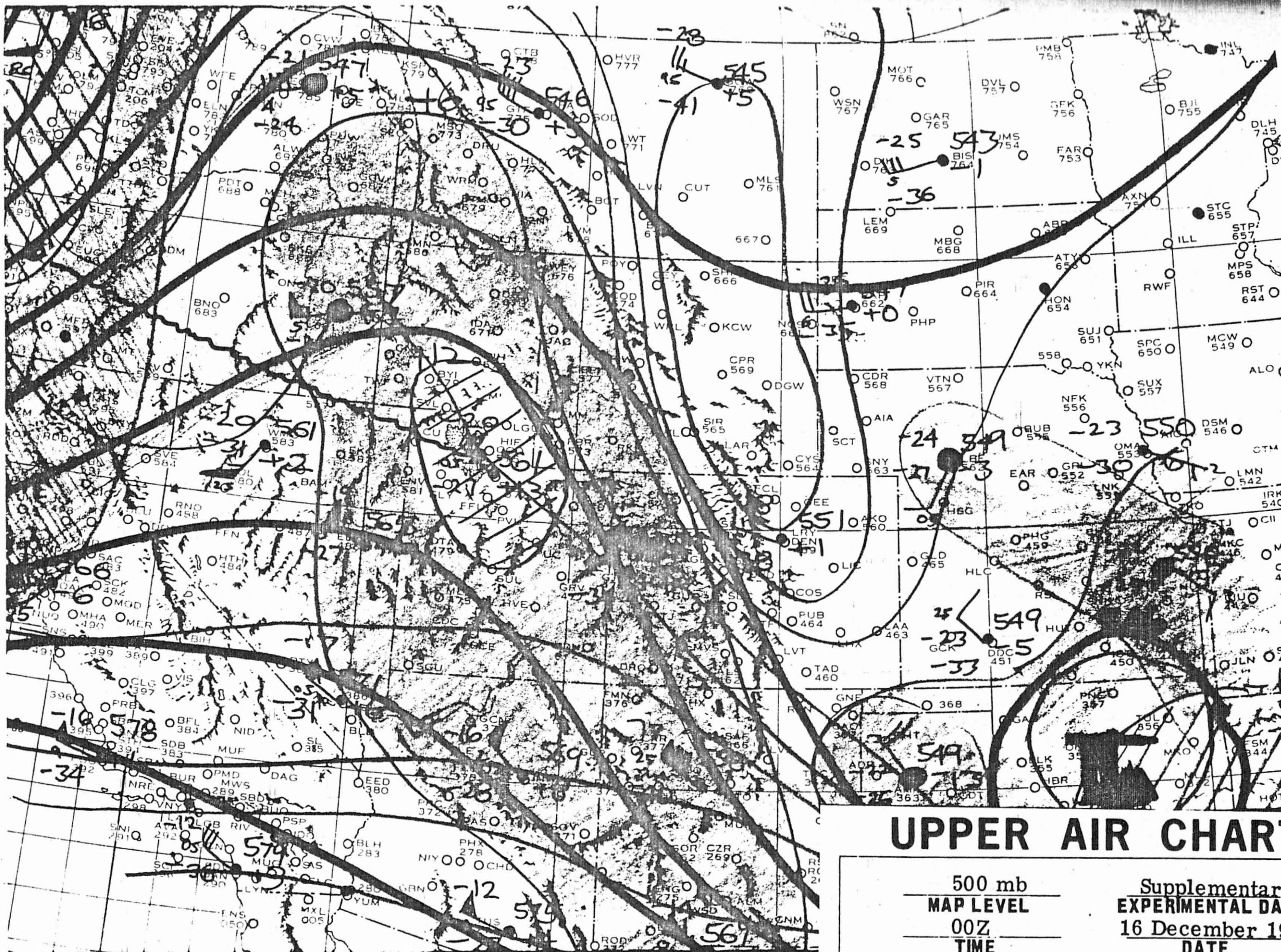


UPPER AIR CHART

700 mb	1
MAP LEVEL	**EXPERIMENTAL DAY**
12Z	15 December 1970
TIME	**DATE**

100 50 0 100 200 300 400 500

MILES



UPPER AIR CHART

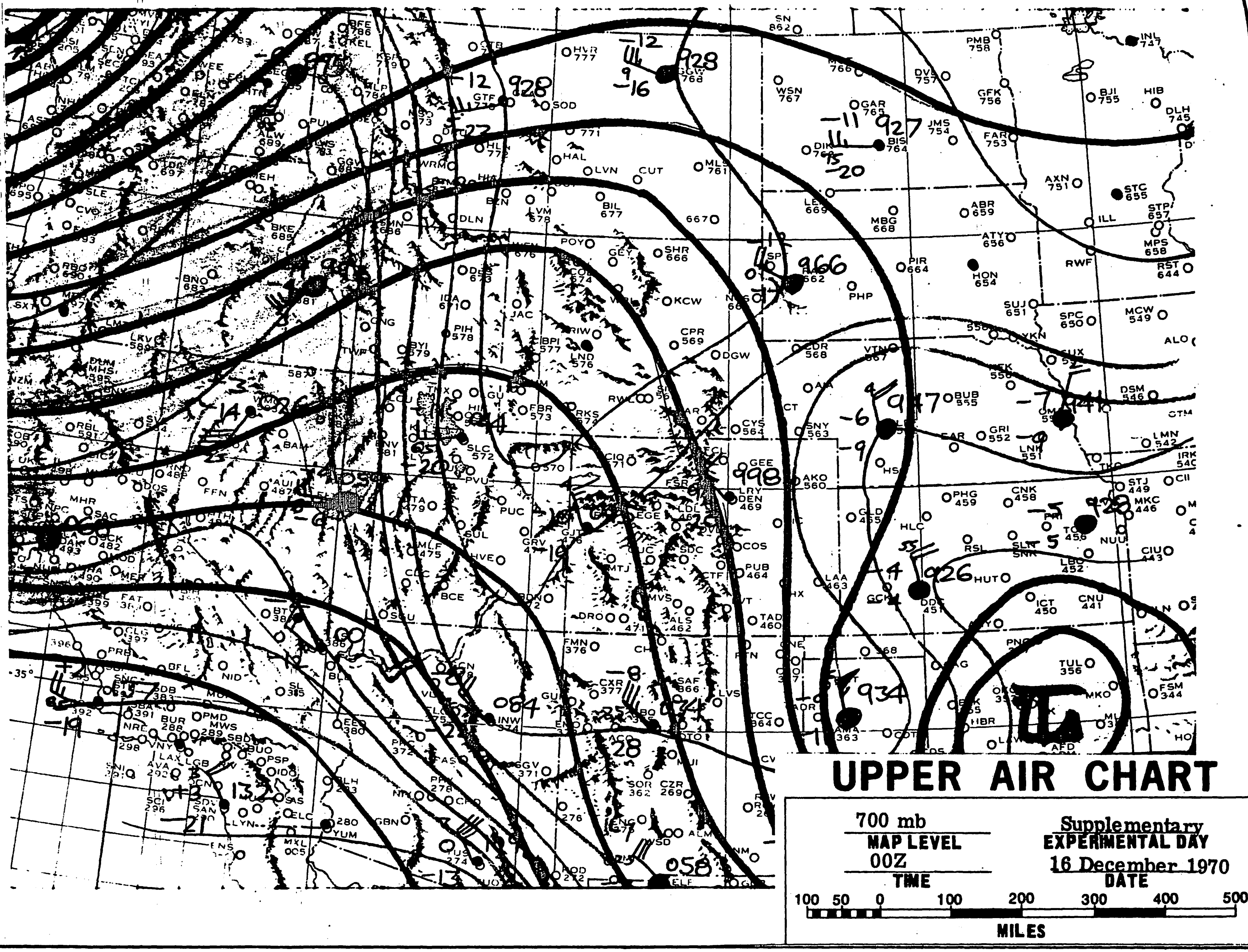
500 mb
MAP LEVEL

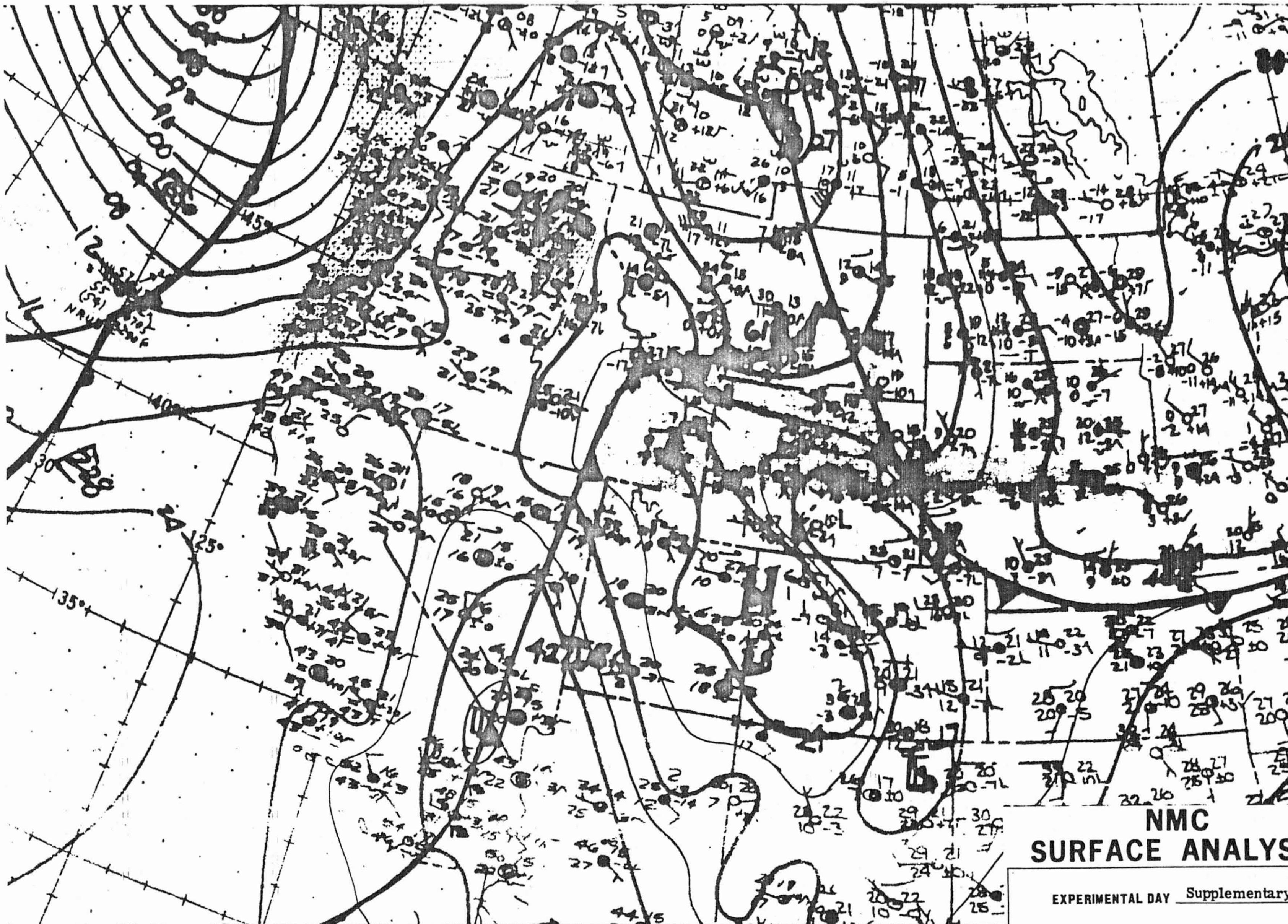
00Z
TIME

Supplementary
EXPERIMENTAL DAY

16 December 1970
DATE

100 50 0 100 200 300 400 500
MILES


UPPER AIR CHART
700 mb
MAP LEVEL
00Z
TIME
Supplementary
EXPERIMENTAL DAY
16 December 1970
DATE
100 50 0 100 200 300 400 500
MILES

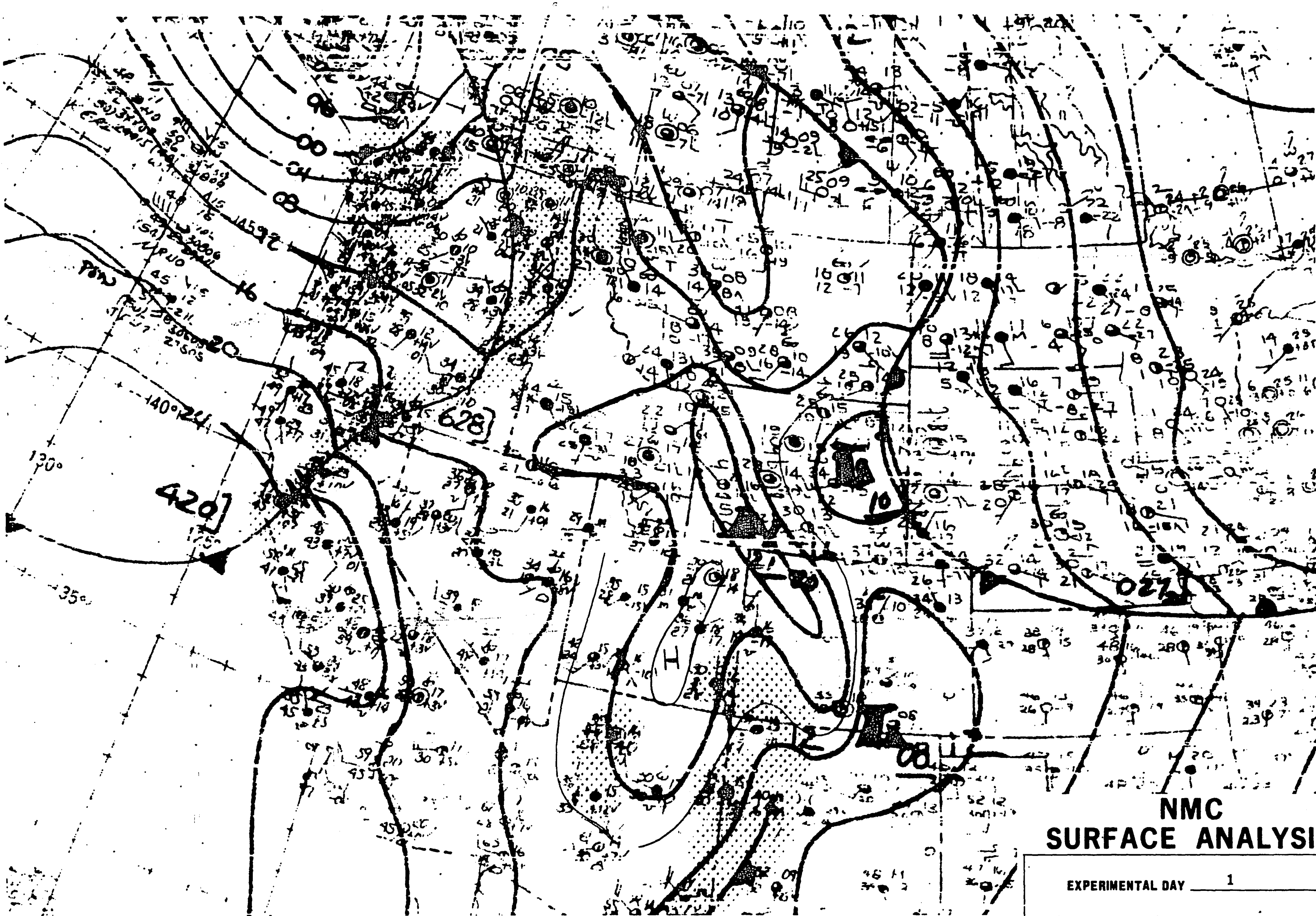


NMC SURFACE ANALYSIS

EXPERIMENTAL DAY Supplementary

14 December 1970 — DATE

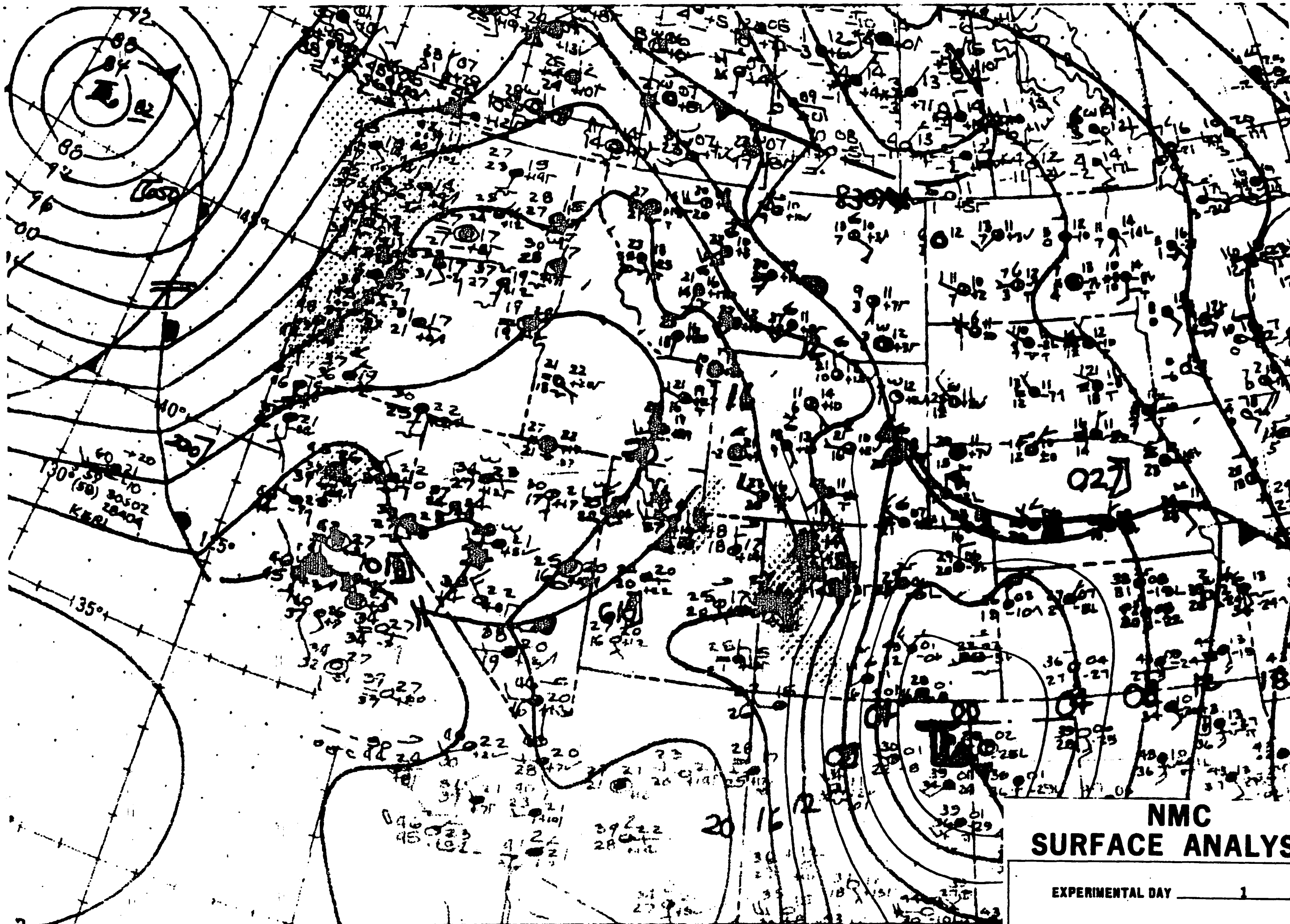
12 Z — TIME



NMC SURFACE ANALYSIS

EXPERIMENTAL DAY 1

15 December 1970 (DATE) 00Z (TIME)

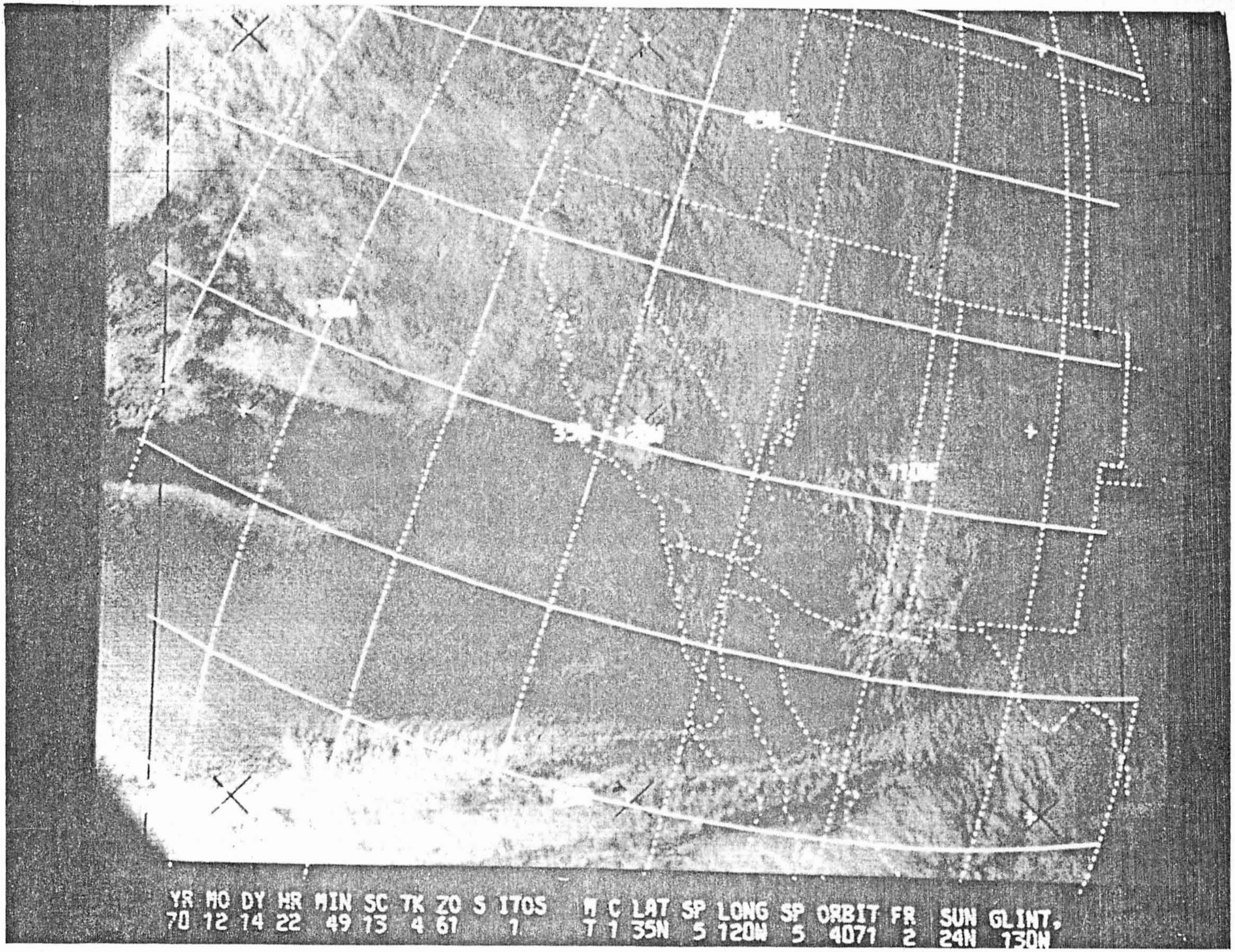


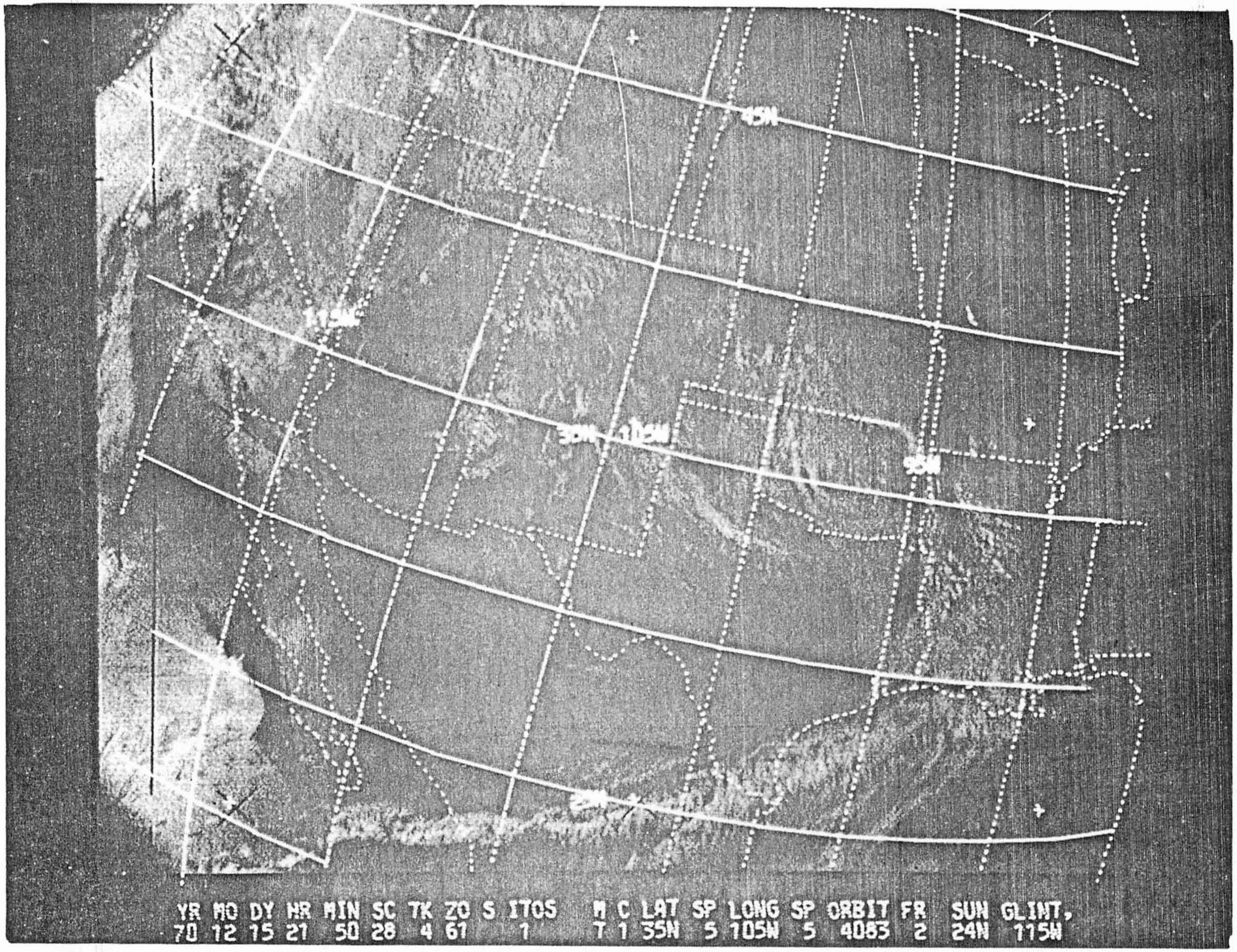
NMC SURFACE ANALYSIS

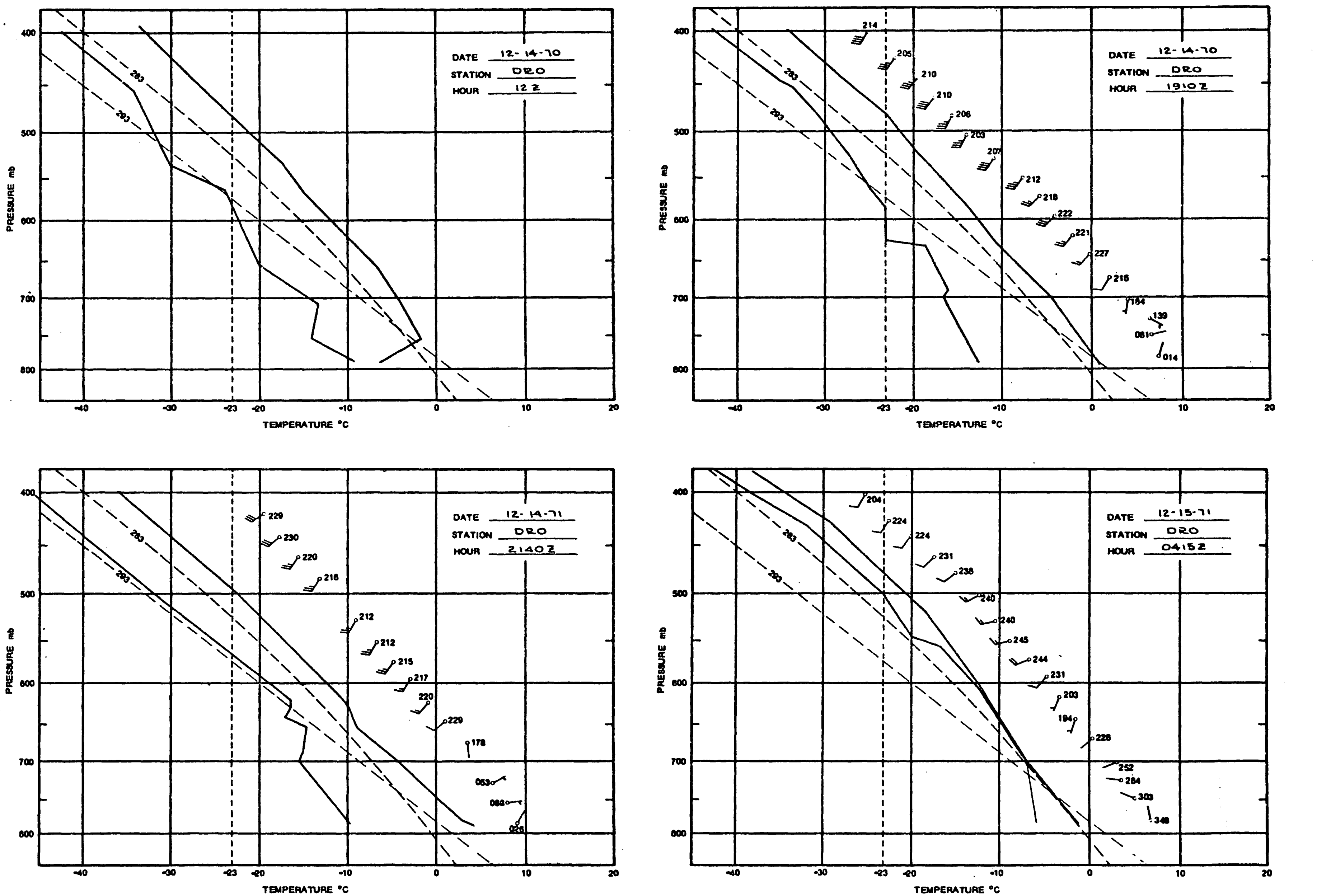
EXPERIMENTAL DAY 1

15 December 1970 — DATE

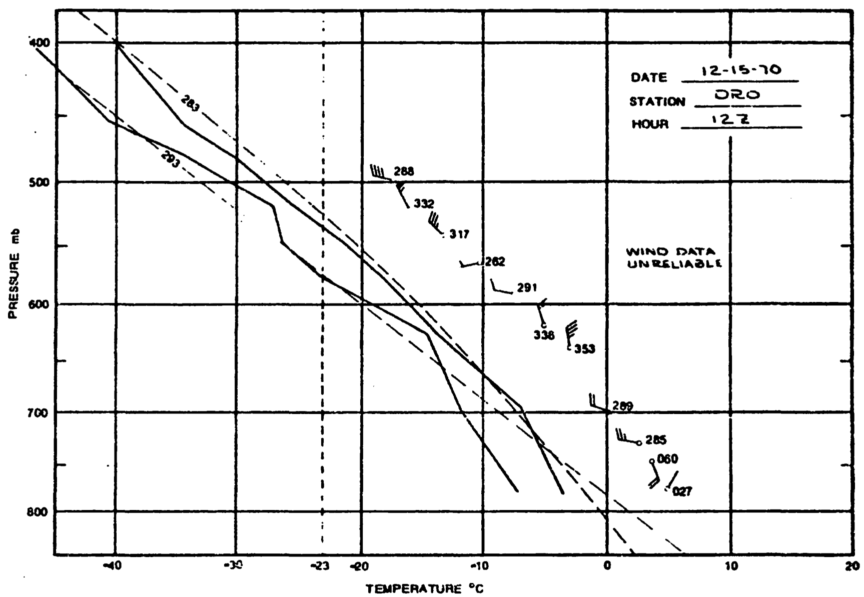
12Z — TIME


YR MO DY HR MIN SC TK ZO S ITOS
70 12 14 22 49 13 4 61 1
M C LAT SP LONG SP ORBIT FR SUN GLINT,
T 1 35N 5 120W 5 4071 2 24N 130W


45N
115W
35N 105W
95W
25N
YR MO DY HR MIN SC TK ZO S ITOS M C LAT SP LONG SP ORBIT FR SUN GLINT,
70 12 15 21 50 28 4 61 1 T 1 35N 5 105W 5 4083 2 24N 115W



Rawinsonde Data, Experimental Day 1
(Sheet 1 of 2)



Rawinsonde Data, Experimental Day 1
(Sheet 2 of 2)

DRY BULB TEMPERATURE, °C

PRESSURE IN MILLIBARS					
		-49.5	-51.5		
		-45.8	-47.8		
		-41.9	-44.5		
		-38.5	-40.9	-36.5	
		-34.6	-37.7	-34.2	
420.0	-38.0	-30.2	-36.1	-31.6	-31.0
440.0	-35.8	-27.4	-32.9	-29.0	-28.7
460.0	-33.6	-25.0	-29.9	-26.1	-26.5
480.0	-31.1	-22.7	-27.5	-23.3	-23.9
500.0	-28.5	-20.5	-25.3	-21.4	-21.5
520.0	-25.9	-18.4	-22.7	-20.1	-19.2
540.0	-23.3	-17.1	-20.5	-18.3	-17.1
560.0	-20.8	-15.6	-18.6	-16.0	-15.5
580.0	-18.6	-14.3	-11.4	-14.1	-13.7
600.0	-16.9	-12.7	-1.3	-12.2	-11.8
620.0	-15.2	-11.3	-12.4	-11.1	-10.0
640.0	-13.3	-11.2	-10.8	-10.0	-8.3
660.0	-11.3	-9.6	-9.7	-8.6	-6.6
680.0	-9.2	-7.9	-8.5	-6.4	-5.4
700.0	-7.4	-7.1	-6.8	-4.6	-4.2
720.0	-6.1	-5.3	-4.6	-4.4	-3.2
740.0	-4.9	-3.7	-2.0	-4.1	-2.4
760.0	-3.7	-3.0	-.6	-1.1	-2.1
780.0	-2.5	-1.6	1.5	0.3	-4.8
793.0	-3.6	1.6	4.0	1.7	-6.5

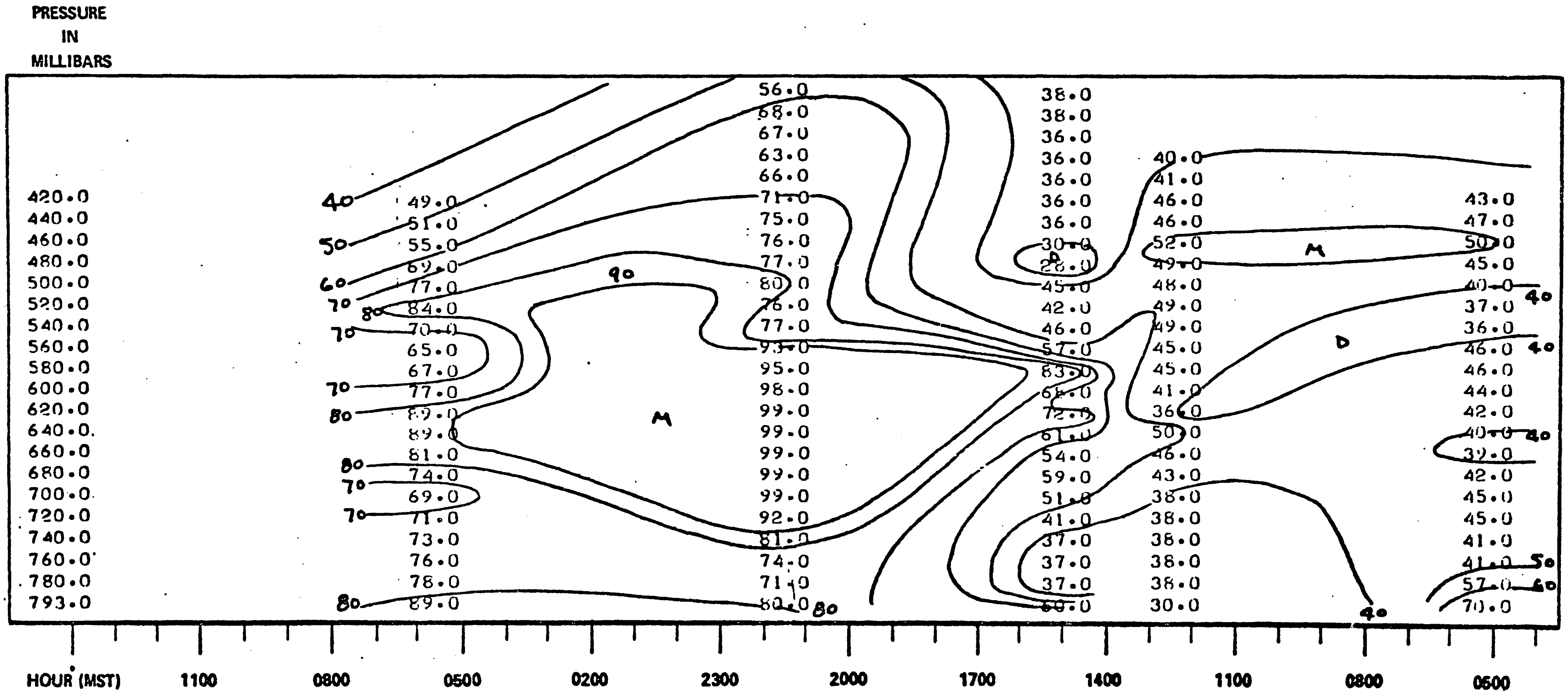
HOUR (MST) 1100 0800 0500 0200 2300 2000 1700 1400 1100 0800 0500

DATE 15 December 1970

DATE 14 December 1970

EXPERIMENTAL DAY 1

RELATIVE HUMIDITY, PERCENT (%)

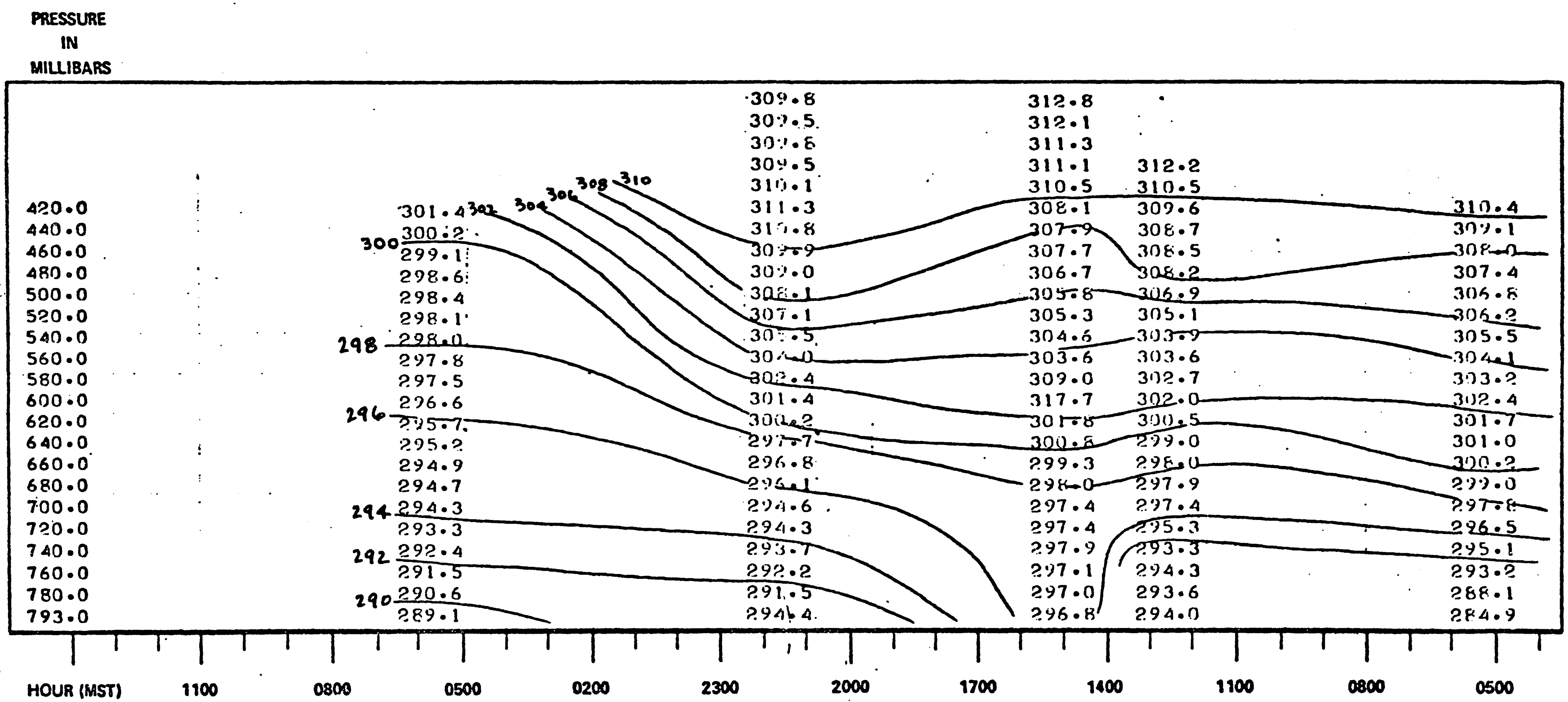


DATE 15 December 1970

DATE 14 December 1970

EXPERIMENTAL DAY 1

DRY BULB POTENTIAL TEMPERATURE, °K



DATE 15 December 1970 **DATE** 14 December 1970

EXPERIMENTAL DAY 1

WET BULB POTENTIAL TEMPERATURE, °K

PRESSURE IN MILLIBARS					
		285.5	286.5		
		285.4	286.3		
		285.5	286.0		
		285.5	286.0	286.5	
		285.8	285.9	286.0	
420.0	282.3	286.3	285.0	285.7	286.0
440.0	281.9	286.3	285.1	285.4	285.6
460.0	281.4	286.1	285.2	285.4	285.2
480.0	281.3	286.0	285.0	285.5	285.1
500.0	281.3	285.9	284.5	285.1	285.0
520.0	281.4	285.7	284.4	284.4	284.9
540.0	281.4	285.2	284.2	284.1	284.8
560.0	281.5	285.2	284.0	284.1	284.3
580.0	281.5	284.8	287.6	283.9	284.1
600.0	281.5	284.8	292.2	283.8	284.0
620.0	281.6	284.6	284.2	283.2	283.8
640.0	281.6	283.5	283.8	282.9	283.7
660.0	281.7	283.5	283.1	282.5	283.5
680.0	281.7	283.6	282.9	282.7	283.3
700.0	281.7	283.1	282.6	282.6	283.0
720.0	281.6	283.1	282.7	281.7	282.6
740.0	281.5	282.7	283.1	280.8	282.0
760.0	281.4	281.9	283.0	281.7	281.1
780.0	281.3	281.7	283.3	281.6	278.7
793.0	280.8	284.5	285.0	281.7	277.2

HOUR (MST) 1100 0800 0500 0200 2300 2000 1700 1400 1100 0800 0500

DATE 15 December 1970 DATE 14 December 1970

EXPERIMENTAL DAY 1

THIS CROSS SECTION IS
RELATIVE HUMIDITY (PCT)

PRES.	TUSOM	INWOM	GJTOM
30.	23.0	4.0	4.0
32.	23.0	7.0	8.0
34.	22.0	11.0	16.0
36.	22.0	17.0	29.0
38.	23.0	27.0	[illegible]
40.	23.0	47.0	54.0
42.	24.0	48.0	58.0
44.	25.0	49.0	[illegible]
46.	26.0	54.0	47.0
48.	27.0	[illegible]	54.0
50.	28.0	63.0	[illegible]
52.	35.0	54.0	97.0
54.	54.0	47.0	[illegible]
56.	72.0	50.0	[illegible]
58.	78.0	53.0	43.0
60.	82.0	45.0	43.0
62.	85.0	45.0	[illegible]
64.	88.0	55.0	91.0
66.	94.0	66.0	[illegible]
68.	94.0	[illegible]	79.0
70.	93.0	91.0	71.0
72.	88.0	93.0	62.0
74.	84.0	95.0	55.0
76.	80.0	98.0	49.0
78.	76.0	100.0	44.0
80.	66.0	92.0	[illegible]
82.	61.0	63.0	[illegible]
84.	55.0	14.0	45.0
86.	51.0	999.0	999.0
88.	47.0	999.0	999.0
90.	44.0	999.0	999.0
92.	50.0	999.0	999.0
94.	999.0	999.0	999.0

THIS CROSS SECTION IS
POTENTIAL TEMPERATURE

PRES.	TUSOM	INWOM	GJTOM
30.	[illegible]	319.3	311.6
32.	328.7	316.2	311.2
34.	324.7	313.3	310.7
36.	320.0	310.6	310.2
38.	315.6	307.9	309.7
40.	311.5	305.0	309.1
42.	309.4	305.0	308.6
44.	307.4	304.1	308.0
46.	305.5	303.5	307.1
48.	303.7	303.0	306.3
50.	302.0	301.7	305.6
52.	300.5	301.0	[illegible]
54.	[illegible]	300.3	[illegible]
56.	299.7	[illegible]	304.2
58.	299.0	299.1	303.8
60.	298.3	298.9	303.1
62.	297.7	298.3	301.6
64.	297.0	297.2	300.0
66.	297.8	296.1	299.0
68.	296.9	295.0	298.3
70.	296.0	294.0	297.7
72.	295.5	293.0	297.1
74.	295.0	292.1	296.5
76.	294.6	291.3	295.9
78.	294.1	290.4	295.2
80.	294.2	288.1	292.3
82.	294.1	285.7	290.3
84.	294.1	285.6	289.7
86.	294.1	999.0	999.0
88.	293.9	999.0	999.0
90.	293.8	999.0	999.0
92.	293.3	999.0	999.0
94.	999.0	999.0	999.0

THIS CROSS SECTION IS
WET BULB POTENTIAL TEMPERATURE

PRES.	TUSOM	INWOM	GJTOM
30.	292.3	288.8	286.1
32.	291.9	287.6	286.0
34.	290.7	286.8	285.8
36.	289.3	285.8	265.7
38.	287.8	284.9	285.6
40.	286.4	283.8	285.4
42.	285.7	283.9	285.3
44.	285.1	283.6	285.1
46.	284.4	283.3	284.9
48.	283.8	283.2	264.7
50.	283.2	282.8	285.0
52.	282.5	282.6	285.0
54.	282.6	282.4	284.9
56.	282.5	282.2	284.5
58.	282.5	282.2	284.4
60.	282.6	282.2	284.3
62.	282.6	282.2	284.4
64.	282.7	282.0	284.7
66.	283.9	281.9	284.4
68.	283.8	282.0	284.2
70.	283.6	282.3	284.0
72.	283.8	282.3	283.7
74.	283.8	282.3	283.4
76.	283.8	282.3	283.1
78.	283.9	282.3	282.8
80.	284.0	280.7	281.1
82.	284.1	278.9	280.2
84.	284.2	279.4	280.4
86.	284.3	999.0	999.0
88.	284.4	999.0	999.0
90.	284.6	999.0	999.0
92.	285.2	999.0	999.0
94.	999.0	999.0	999.0

THIS CROSS SECTION IS
MOIST POTENTIAL TEMPERATURE

PRES.	TUSOM	INWOM	GJTOM
30.	292.3	288.8	286.1
32.	291.9	287.8	286.0
34.	290.7	286.8	285.8
36.	289.3	285.8	265.7
38.	287.8	284.9	285.6
40.	286.4	283.8	285.5
42.	285.7	283.9	285.4
44.	285.1	283.6	285.3
46.	284.4	283.5	285.1
48.	283.8	283.5	285.0
50.	283.2	283.1	285.0
52.	282.8	283.0	285.1
54.	283.1	283.0	285.2
56.	283.0	282.7	285.5
58.	283.0	283.1	285.7
60.	283.0	283.3	285.8
62.	283.0	283.5	285.5
64.	283.1	283.2	285.0
66.	284.2	283.0	284.9
68.	284.1	282.8	285.1
70.	284.1	282.7	285.3
72.	284.3	282.6	285.5
74.	284.6	282.5	265.7
76.	284.9	282.4	285.9
78.	285.3	282.3	286.1
80.	286.0	281.1	284.4
82.	286.7	279.7	283.5
84.	287.4	280.2	283.7
86.	288.2	999.0	999.0
88.	288.8	999.0	999.0
90.	289.5	999.0	999.0
92.	289.9	999.0	999.0
94.	999.0	999.0	999.0

Atmospheric Cross Sections,
Experimental Day 1, 15 December 1970, 00Z

THIS CROSS SECTION IS
RELATIVE HUMIDITY (PCT)

PRES.	MFRIN	WMCIN	ELYIN	ABQIN
30.	4.0	4.0	4.0	4.0
32.	13.0	11.0	11.0	4.0
34.	37.0	[illegible]	[illegible]	4.0
36.	56.0	[illegible]	[illegible]	26.0
38.	62.0	[illegible]	45.0	32.0
40.	69.0	77.0	45.0	31.0
42.	70.0	78.0	45.0	20.0
44.	72.0	78.0	44.0	15.0
46.	74.0	78.0	44.0	33.0
48.	75.0	81.0	44.0	35.0
50.	77.0	84.0	44.0	25.0
52.	78.0	87.0	47.0	25.0
54.	78.0	86.0	49.0	24.0
56.	72.0	83.0	40.0	25.0
58.	[illegible]	[illegible]	[illegible]	54.0
60.	61.0	79.0	[illegible]	52.0
62.	77.0	65.0	99.0	60.0
64.	68.0	57.0	100.0	59.0
66.	61.0	42.0	94.0	57.0
68.	100.0	42.0	85.0	55.0
70.	100.0	47.0	78.0	53.0
72.	100.0	51.0	67.0	67.0
74.	100.0	42.0	[illegible]	71.0
76.	[illegible]	61.0	55.0	91.0
78.	43.0	[illegible]	53.0	89.0
80.	46.0	54.0	51.0	82.0
82.	54.0	54.0	999.0	77.0
84.	60.0	52.0	999.0	999.0
86.	61.0	51.0	999.0	999.0
88.	57.0	999.0	999.0	999.0
90.	54.0	999.0	999.0	999.0
92.	53.0	999.0	999.0	999.0
94.	76.0	999.0	999.0	999.0
96.	68.0	999.0	999.0	999.0
98.	999.0	999.0	999.0	999.0

THIS CROSS SECTION IS
POTENTIAL TEMPERATURE

PRES.	MFRIN	WMCIN	ELYIN	ABQIN
30.	317.9	318.1	318.1	323.2
32.	317.1	316.9	316.8	317.6
34.	316.3	315.7	315.5	[illegible]
36.	315.2	314.5	314.6	312.1
38.	314.0	313.5	314.4	311.2
40.	312.8	312.8	314.1	310.4
42.	310.7	312.0	312.7	309.6
44.	308.7	311.3	311.5	308.9
46.	306.8	310.6	310.2	306.3
48.	304.9	308.7	309.0	304.9
50.	303.2	306.8	307.8	302.0
52.	301.9	305.7	306.6	302.4
54.	300.6	304.1	[illegible]	302.6
56.	299.4	302.2	[illegible]	302.9
58.	298.2	300.4	[illegible]	300.4
60.	297.0	298.7	291.7	297.8
62.	295.9	296.7	292.1	298.8
64.	294.7	294.8	291.4	298.0
66.	293.6	292.9	290.6	297.2
68.	293.3	291.4	290.5	296.5
70.	293.1	290.2	290.4	295.7
72.	291.9	289.5	290.1	294.6
74.	288.6	288.7	289.6	292.7
76.	286.3	288.2	289.7	291.3
78.	284.6	288.0	289.6	290.6
80.	283.7	287.7	289.4	290.1
82.	282.8	287.4	999.0	289.6
84.	281.9	287.1	999.0	999.0
86.	281.5	286.5	999.0	999.0
88.	281.6	999.0	999.0	999.0
90.	281.7	999.0	999.0	999.0
92.	281.5	999.0	999.0	999.0
94.	278.8	999.0	999.0	999.0
96.	277.5	999.0	999.0	999.0
98.	999.0	999.0	999.0	999.0

THIS CROSS SECTION IS
WET BULB POTENTIAL TEMPERATURE

PRES.	MFRIN	WMCIN	ELYIN	ABQIN
30.	288.3	288.4	288.4	290.0
32.	288.1	288.0	288.0	288.2
34.	287.9	287.6	287.6	287.3
36.	287.5	287.3	287.3	286.4
38.	287.1	287.0	287.4	286.2
40.	286.8	286.8	287.3	286.0
42.	286.1	286.6	286.9	285.9
44.	285.4	286.5	286.5	285.7
46.	284.8	286.4	286.1	284.7
48.	284.2	285.9	285.8	284.2
50.	283.6	285.4	285.4	283.2
52.	283.2	285.2	285.1	283.6
54.	282.8	284.7	284.8	283.9
56.	282.4	284.0	286.2	284.0
58.	282.1	283.4	279.5	282.9
60.	281.8	282.7	278.7	282.6
62.	281.4	281.6	279.5	282.6
64.	280.9	280.6	279.6	282.5
66.	280.4	279.6	279.3	282.3
68.	281.7	279.0	279.4	282.2
70.	282.0	278.6	279.5	282.0
72.	281.7	278.5	279.3	282.2
74.	279.8	276.5	279.2	282.4
76.	277.1	278.5	279.3	282.0
78.	275.9	278.6	279.5	282.0
80.	275.7	278.7	279.7	281.8
82.	275.5	278.8	999.0	281.6
84.	275.3	278.9	999.0	999.0
86.	275.5	278.8	999.0	999.0
88.	275.7	999.0	999.0	999.0
90.	276.0	999.0	999.0	999.0
92.	276.2	999.0	999.0	999.0
94.	[illegible]	999.0	999.0	999.0
96.	275.4	999.0	999.0	999.0
98.	999.0	999.0	999.0	999.0

THIS CROSS SECTION IS
MOIST POTENTIAL TEMPERATURE

PRES.	MFRIN	WMCIN	ELYIN	ABQIN
30.	288.3	288.4	288.4	290.0
32.	288.1	288.0	288.0	288.2
34.	287.9	287.6	287.6	287.3
36.	287.6	287.3	287.3	286.4
38.	287.2	287.0	287.4	286.2
40.	286.9	286.9	287.4	286.0
42.	286.2	286.8	287.1	285.9
44.	285.6	286.7	286.8	285.7
46.	285.0	286.7	286.5	284.8
48.	284.4	286.2	286.3	284.4
50.	283.8	285.6	286.1	283.2
52.	283.5	285.4	285.9	283.7
54.	283.1	285.0	285.7	284.3
56.	282.8	284.4	287.7	284.6
58.	282.5	283.3	280.0	283.8
60.	282.2	283.2	279.1	283.9
62.	282.0	282.5	279.6	283.7
64.	281.7	281.7	279.6	283.7
66.	281.4	280.9	279.4	283.8
68.	281.7	280.4	279.8	283.8
70.	282.0	280.0	280.2	283.9
72.	281.7	280.0	280.4	283.7
74.	279.8	279.9	280.7	282.9
76.	278.6	280.1	281.2	282.4
78.	277.8	280.4	281.7	282.5
80.	277.5	280.8	282.2	282.7
82.	277.3	281.1	999.0	282.9
84.	277.0	281.5	999.0	999.0
86.	277.2	281.6	999.0	999.0
88.	277.9	999.0	999.0	999.0
90.	278.5	999.0	999.0	999.0
92.	278.9	999.0	999.0	999.0
94.	277.0	999.0	999.0	999.0
96.	276.3	999.0	999.0	999.0
98.	999.0	999.0	999.0	999.0

Atmospheric Cross Sections,
Experimental Day 1, 15 December 1970, 12Z