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Final Report

DISTRIBUTION AND DIMENSIONS OF CLOUD COVER AT ALTITUDES ABOVE 20,000 FEET

By: R. H. BLACKMER, JR.

Prepared for:

LOCKHEED MISSILES AND SPACE COMPANY
A GROUP DIVISION OF LOCKHEED AIRCRAFT COMPORATION
P.O. BOX 504
SUNNYVALE, CALIFORNIA

CONTRACT AF 04(647)-787
PURCHASE ORDER 28-4001

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SRI Project No. 4649

Approved: MYRON G. H. LIGDA, MANAGER
AEROPHYSICS LABORATORY

D. R. SCHEUCH, DIRECTOR
ELECTRONICS AND RADIO SCIENCES DIVISION

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ABSTRACT

The research described in this Final Report is directed toward finding methods of specifying the most probable distribution of cloud-top altitudes within areas where high-altitude clouds are likely to exist. During a nine-month period, three cases were studied utilizing cloud photographs from U-2 aircraft and pertinent concurrent meteorological data. The cloud photographs were analyzed by methods developed at Stanford Research Institute to determine the dimensions and distributions of clouds above 20,000 ft. Meteorological data--such as hourly cloud observations, six-hourly synoptic charts, twelve-hourly radiosonde ascents, and hourly summaries of radar echoes--were analyzed to determine the state of the atmosphere as well as time changes in atmospheric conditions related to cloud cover.

The profiles and plan views of cloud-top altitudes showed that the taller convective clouds occurred in clusters. Surrounding these clusters were much lower tops and even clear areas between the more widely spaced clusters. Cirrus layers, apparently produced by the merging of anvils from individual thunderstorms in the cluster, extended downwind for varying distances, depending on the stage of development of the cluster. These layers of cirrus did not exceed the height of the tropopause and in areas of nonpersistent convection were well below the tropopause level. Maximum cloud tops were found to penetrate the tropopause by as much as 10,000 ft and radar echo penetrations of 15,000 ft were noted in moist tropical air.

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ILLUSTRATIONS

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PROJECT PERSONNEL

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1 INTRODUCTION

This final report presents the results of studies of cloud cover at altitudes above 20,000 ft Two case studies are illustrated by appropriate meteorological data and photogrammetric analyses of clouds from U-2 photographs. The case studies are the second and third analyzed under the contract The first case study was presented in Technical Note 64-1.[1]* The first case study was concerned with air mass (non-frontal) cloud cover and compared the distributions of thunderstorms over southeastern United States with those over the mountainous southwestern states. The case studies in this report are concerned with squall-line thunderstorms (31 May 1962 situation) and with frontal cloudiness at the boundary of a cold air mass (29 April 1960). The three cases, therefore, provide information on cloud cover associated with four different sets of atmospheric conditions.

The objectives of the study are given by the following statement of work:

> The analyses and measurements shall be performed in order to develop data, and graphical and technical information, as follows:
>
> (1) Profiles of the vertical extent of cloud cover (altitude of tops) along and at appropriate distances on either side of the flight track within areas where cloud tops are at or above 20,000 feet msl.

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*References are given at the end of the report

(2) Relationship of the cloud top altitudes of the above profiles with such factors as:

(a) Air mass and time of day

(b) Height of tropopause

(c) Height of underlying terrain

(d) Temperature and stability of the atmosphere.

(3) The spacing, areal extent, and cloud top altitudes of concomitant areas of thunderstorms insofar as they may be related to storm systems, fronts, or other synoptic features, such as jet streams.

The ultimate goal of the research is finding methods of specifying the most probable distribution of cloud-top altitudes within areas where high-altitude clouds are likely to exist.

2. CLOUD DISTRIBUTIONS AND DIMENSIONS

2.1 GENERAL

In the analysis of the two cases, the U-2 film was examined to locate areas where the cloud cover extended above 20,000 ft msl. Frames of film containing images of such clouds were then subjected to photogrammetric analyses (the photogrammetric techniques were presented in Ref. 2) to determine the altitudes of the cloud tops. Profiles of cloud-top altitudes were then constructed for clouds along the flight track and along lines 60 miles either side of the flight track. In addition to the profiles, a plan view of the cloud cover was also drawn to provide more detail on the tops not shown on the profiles.

For each case study a series of meteorological charts was prepared to show atmospheric conditions within and adjacent to the areas of high altitude clouds. These charts are presented in the Appendix.

2.2 SQUALL LINE OF 31 MAY 1962

2.2.1 Flight Information

On 31 May 1962, a U-2 aircraft departed from Edwards AFB, California, at 1942 GMT. The aircraft arrived in the vicinity of Amarillo, Texas at 2145 GMT and for the following two hours made several passes in a north-south direction to photograph a squall line. After the two hours over the squall line, the aircraft returned to Edwards AFB and landed at 0155 GMT 1 June 1962. Aircraft altitude while over the squall line was in the vicinity of 65,000 ft.

Figure 1 shows the track of the U-2, the locations of high altitude clouds, and the stations used in the construction of atmospheric cross sections. Table 1 identifies the stations.

The cloud and weather observations on Fig. 1 show widespread high-altitude cloud cover over all areas of the country except the southwestern states. The thunderstorm and cumulonimbus symbols

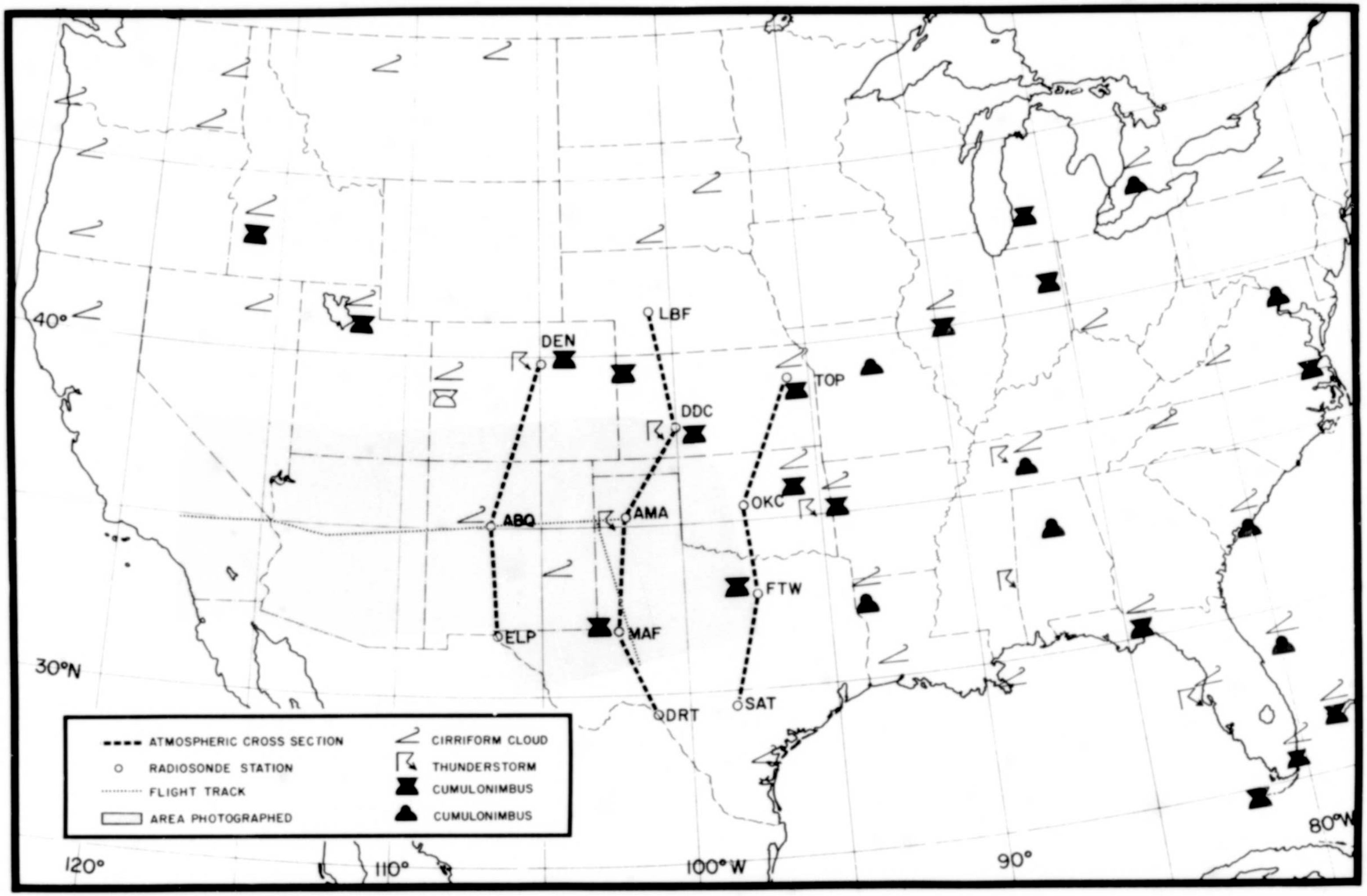

FIG. 1 AREA OF ANALYSIS RELATIVE TO LARGE-SCALE THUNDERSTORM DISTRIBUTION ON 31 MAY 1962

Table 1

WEATHER STATIONS SHOWN IN FIG. 1

DEN, Denver Colorado	MAF, Midland, Texas
ABQ, Albuquerque, New Mexico	DRT, Del Rio, Texas
ELP, El Paso, Texas	TOP, Topeka, Kansas
LBF, North Platte, Nebraska	OKC, Oklahoma City, Oklahoma
DDC, Dodge City, Kansas	FTW, Fort Worth, Texas
AMA, Amarillo, Texas	SAT, San Antonio, Texas

form a general line extending from the Great Lakes through Kansas into Idaho. This line of thunderstorms lies along a cold front. To the north and west of the line, cirriform cloud without thunderstorms is shown. South of the cold front, there are thunderstorms reported over the southeast and south central parts of the country. These thunderstorms, except for those over southern Florida, are associated with squall lines. The area of squall line thunderstorms photographed by the U-2 lies along the western edge of the moist tropical air. This squall line over northern and west central Texas is occurring along a "dew-point" front--a line across which dew points show a discontinuity of as much as 50 or 60°C. Henry and Thompson[3] made a study of cloud cover associated with dew-point fronts using TIROS I photographs. They found that cloud cover varied with direction of movement of the front; intensified cloud activity and even thunderstorms and tornadoes appeared to be associated with westward surges of the dew-point front.

2.2.2 Cloud Distribution

The U-2 flew on a north-south track and circled over some portions of the squall line several times. Two segments of the track that provided the straightest and most continuous coverage of the squall line were selected from the complex flight track for analysis. Cloud cover shown by photographs taken during these two portions of the flight were then analyzed in detail to determine cloud-top altitudes and cloud locations. The cloud pattern shown by the photographs was quite complex. At the southern end of the squall line, individual isolated convective cells could be identified. Farther north, the individual cells were generally masked by m tilayered cirriform cloud cover. At the northern end of the area photographed, there was a single layer of smooth cirrus along the flight track with a higher layer visible 80 miles west of the track. Farther east, about 100 miles away, distant tops of another area of large thunderstorms were visible.

Since the U-2 flew approximately along the center line of the squall line, and the width of the cloud cover associated with portions of the line was only 80 or 90 miles, profiles of cloud top altitudes 60 miles either side of the track contained very little cloud. To portray the cloud cover more adequately, a plan view of the distribution and top altitude was constructed to supplement the profiles. The profiles are shown in Fig. 2 and the plan view in Fig. 3. Both profiles and plan view are drawn to scale; that is, the heights and widths of cloud elements or cloud areas have been plotted exactly to the dimensions determined by measurements.

The profile along the track shows features mentioned previously, i.e., the transition from more isolated clouds at the south to a uniform cirrus layer at the north end of the area photographed.

Also shown is a general northward decrease in cloud top altitude. This decrease is consistent with the lowering of the tropopause toward the north. The level of the tropopause is indicated on the temperature scales at Midland (MAF) and Amarillo (AMA) and is located at the level where the temperature is plotted at the left side of the scale. At Midland the tropopause is at 42,000 ft, while at Amarillo it is just below 40,000 ft. Comparison of cloud-top altitudes with the tropopause shows that only two of the clouds shown on the profile have tops extending above the tropopause and this extension was only 1000 to 1500 ft.

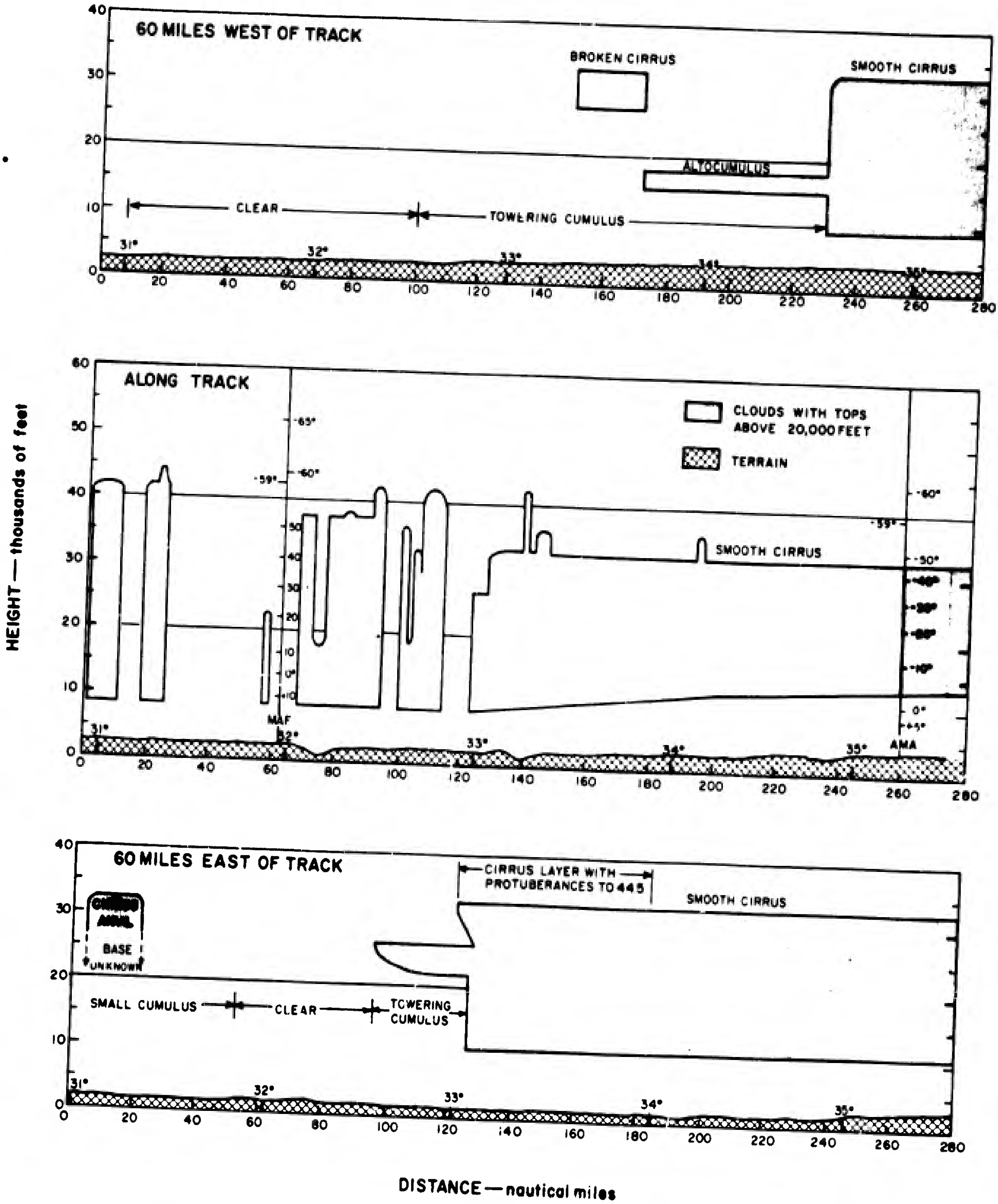

FIG. 2 PROFILES OF SQUALL LINE CLOUD COVER ON 31 MAY 1962

The profile 60 miles west of the flight track shows patches of cirrus and a layer of altocumulus. The cirrus cloud did not originate from the squall line thunderstorms but instead was apparently produced by the thunderstorms over New Mexico and Colorado. The top of the layer of cirrus was at an altitude of 33,000 ft or about 7000 ft below the tropopause.

The profile 60 miles east of the track shows primarily the cirrus cloud blowing eastward from the tops of the squall line thunderstorms. The tops of the cirrus were around 33,000 ft except as noted (near 33°N) where a lower layer was evident with tops at 26,500 ft. Between 33°N and 34°N, the upper surface of the cloud layer was not smooth; a number of convective-appearing protuberances were apparent in the photographs. These protuberances extended as much as 10,000 ft above the general level of the top of the layer. None of these protuberances, however, was located along the line of the profile. The tropopause height in the vicinity of the protuberances was 41,000 ft, so some tops were penetrating the tropopause by about 3,500 ft.

Greater detail on the distribution of high altitudes is given by the plan view of cloud cover in Fig. 3. Included on the figure are latitude and longitude lines and the two segments of the flight track from which photographs were analyzed. Lines on the figure were drawn to show the following characteristics of cloud cover:

(1) Boundary between cloud and no cloud (clear);

(2) Boundaries between cumulus less than 20,000 ft tall and cumulonimbus;

(3) Boundaries of cirrus layers; and

(4) Outlines of individual cloud elements exceeding 20,000 ft.

The heights (in thousands of feet) are indicated for the individual cloud elements. When a layer of cloud was observed and

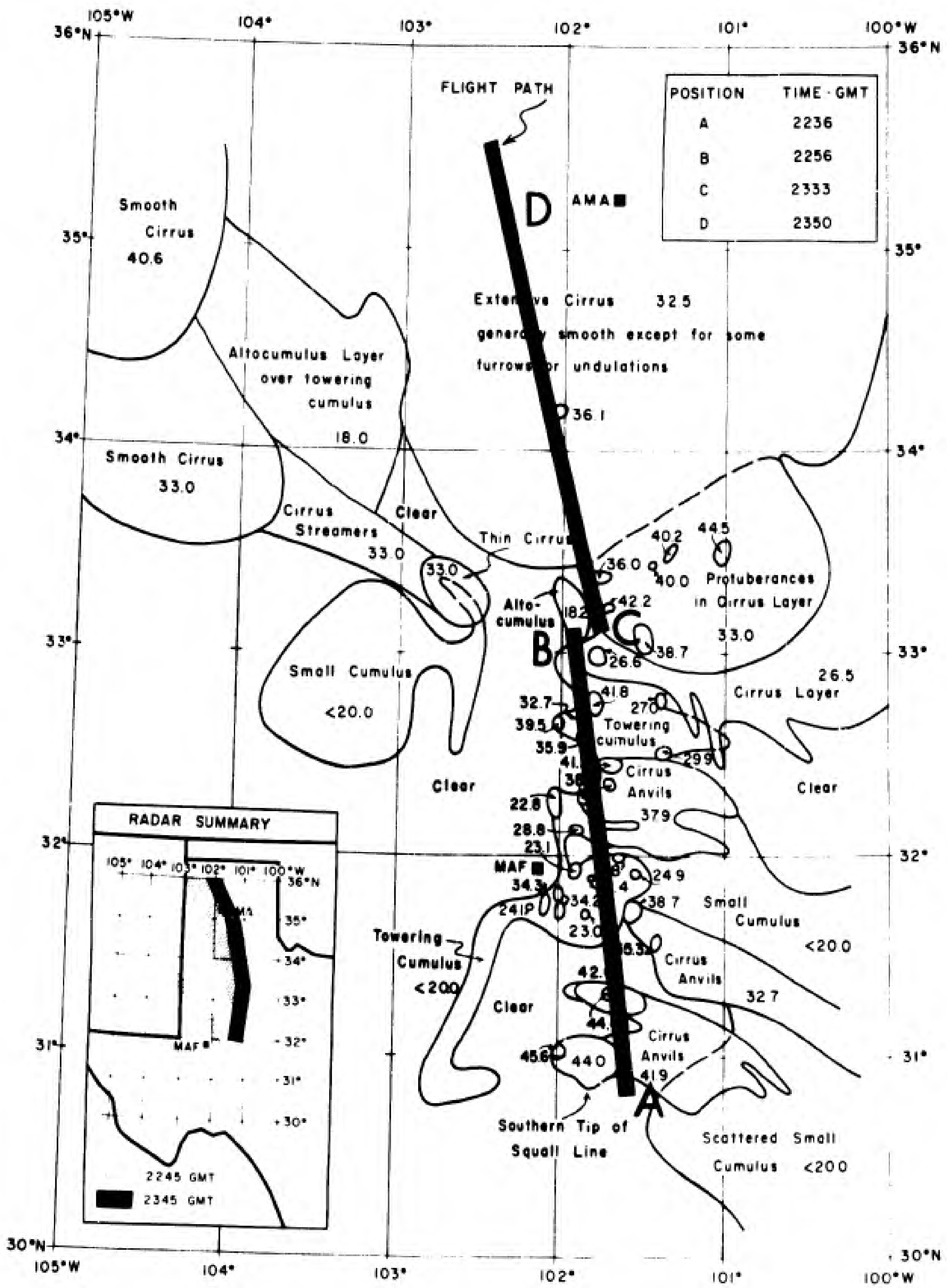

FIG. 3 PLAN VIEW OF SQUALL LINE CLOUD COVER ON 31 MAY 1962

several measurements at different points showed uniform heights (heights did not vary by more than 1000 ft) a single height was given for the entire layer. Several of the layers had protuberances extending well above the general level of the top of the layer. An example is the region around 33.5°N, 101°W. The boundaries and heights of major protuberances in this area are noted within the boundaries of the layer.

An inset at the lower left of the figure shows locations of radar echoes at 2245 and 2345 GMT. The radar pattern at 2245 GMT was interpreted as two lines of echoes. Without the original radarscope records, the reason for this interpretation is not apparent. Probably some of the small cumulus near 33°N, 103°W contained showers that were detected by radar. The U-2 analysis showed only a single band of large clouds. This band extends nearly north-south and lies between 101° and 102°W. Within this band numerous tops extended above 40,000 ft. The higher tops generally appear in clusters with much lower tops between the clusters. The anvils associated with the thunderstorms at the south end of the squall line extend eastward 60 or so miles from the convective columns. These individual anvils show considerable variability in altitude The top of the southernmost anvil was measured at 41,900 ft. The next anvil to the north was only 32,700 ft. The large area of cirrus to the north had a top at 32,500 ft. At the northwest corner of the area analyzed a higher layer of cirrus was measured at 40,600 ft. These large areas of cirrus probably resulted from the merging of many individual anvils during a period of many hours and should persist for a considerable period of time after the convective activity had ceased.

Figure 4 shows three U-2 photographs of the squall line. In these photographs the horizon at the top is the right (or eastern) horizon, at the bottom the left or western horizon, and the center of each photograph is the point directly beneath the aircraft. Latitude and longitude of the point are given below each photograph. Figure 4(a) shows the extensive cirrus toward the north end of the area photographed. The top of the layer appears relatively smooth except for some small

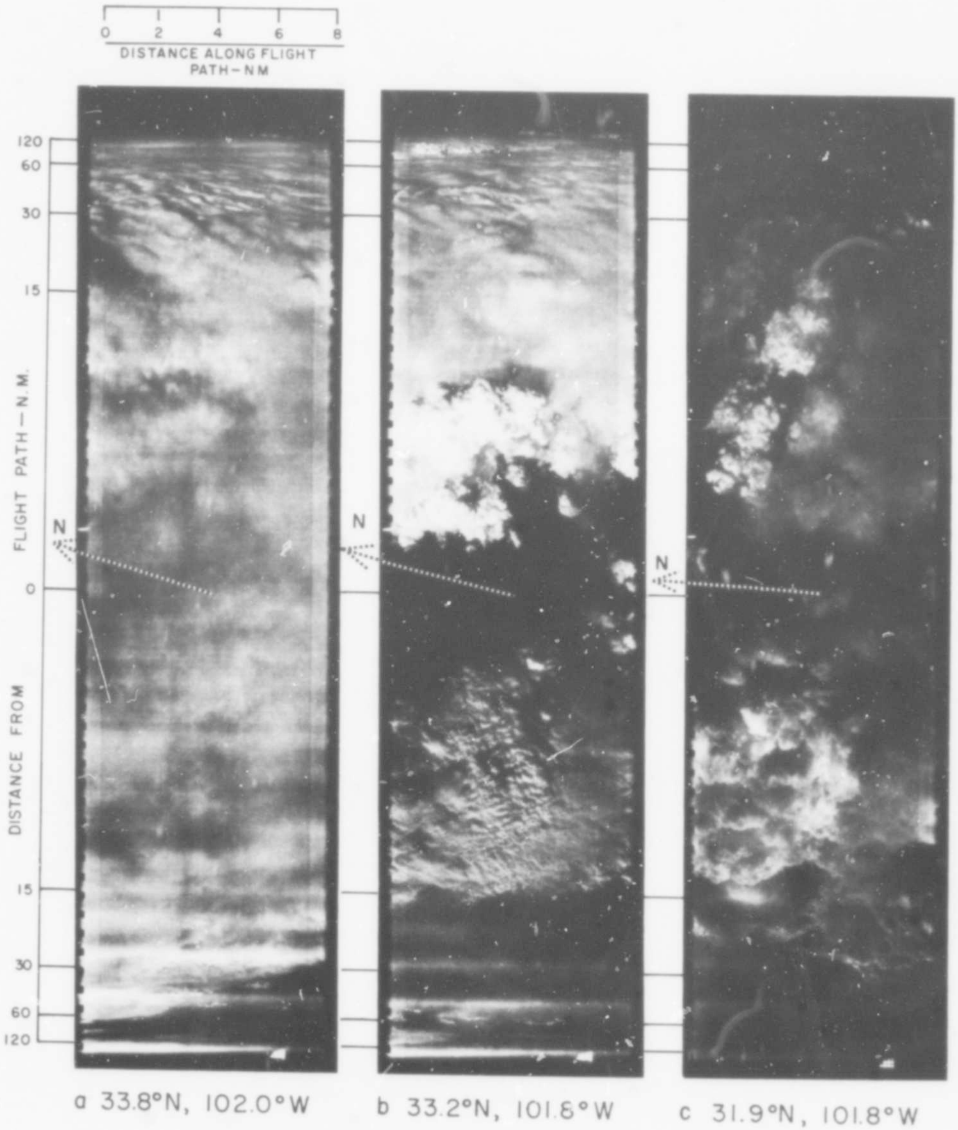

FIG. 4 U-2 PHOTOGRAPHS OF SQUALL LINE CLOUDS ON 31 MAY 1962

undulations or furrows near the top of the photograph. Figure 4(b) shows the cloud cover near the center of the area photographed. A small patch of altocumulus is visible just below the center of the photograph. Just above the center a convective tower marks the edge of the extensive cloud layer. Nearly at the top of the photograph, just left of the centerline, a bright white area of protruding tops is visible. Thunderstorms are visible on the horizon, far to the east Figure 4(c) shows the clouds near the south end of the squall line In this photograph the isolated nature of the clouds is apparent--no clouds or only small cumulus occupy the space between the central part of the photograph and the horizons. At the top of the photograph, distant thunderstorms are visible on the horizon

These three photographs illustrate the appearance and variability of cloud cover as seen from above They do not show all the complexity of the cloud cover, however It is necessary to view pairs of photographs stereoscopically to appreciate much of the fine structure of the cloud elements and to distinguish (without making detailed measurements) the differences in heights between adjacent cloud elements.

2.2.3 Summary of 31 May 1962 Case Study

On 31 May 1962 there was extensive thunderstorm activity within a tropical air mass over the southern and eastern states. The thunderstorm activity occurred along a cold front at the northern boundary of the tropical air and along four squall lines within the tropical air It was one of these squall lines over which the U-2 flew and collected a series of cloud photographs. The cloud photographs were analyzed to determine the dimensions and distributions of the squall line cloud cover The cloud cover ranged from isolated cumulonimbus at the southern end of the squall line to an extensive layer of cirrus within which no distinct thunderstorm tops were visible at the north end of the squall line Cloud top altitudes varied from 45,600 ft at the southernmost thunderstorm in the squall line to 32,500 ft for the uniform cirrus layer to the north The cirrus clouds were in multiple layers at levels from 26,500 ft to 41,900 ft. This latter height corresponded closely to the level of the tropopause over the area. Higher tops were measured by radar at locations to the north and east of the squall line. The radar heights indicated tropopause penetrations of up to 15,000 ft. Penetrations of this magnitude are not uncommon, as indicated in a study by Pautz and Doloresco.[4] They found an average penetration of 10,140 ft for 42 echoes associated with tornadoes and 12,600 ft for 33 echoes associated with hail 1-1/4 to 4 inches in diameter. These penetrations apply to data for the southern plains during May. They also presented data for other areas for the months February to August to show the variability of average penetration.

2.3 COLD FRONT OF 29 APRIL 1960

2.3.1 Flight Information

The U-2 flight on 29 April 1960 originated at Edwards AFB, California at 1818 GMT. During the four hour and nineteen minute duration of the flight the aircraft followed an easterly track to Winslow, Arizona, northerly to Grand Junction, Colorado, then southwestward back to Edwards AFB, California. Figure 5 shows the flight track, the area of analysis (Table 2 identifies the weather stations on the figure) and the gross distribution of cloud cover for this case.

Table 2

WEATHER STATIONS SHOWN IN FIG. 5

SMO	Santa Monica, California
LAS	Las Vegas, Nevada
GJT	Grand Junction, Colorado
DEN	Denver, Colorado

The figure shows that little high-altitude cloud cover was reported by the surface observers on this date. The U-2, however, did fly over thunderstorms and other high-altitude cloud cover on the return leg of

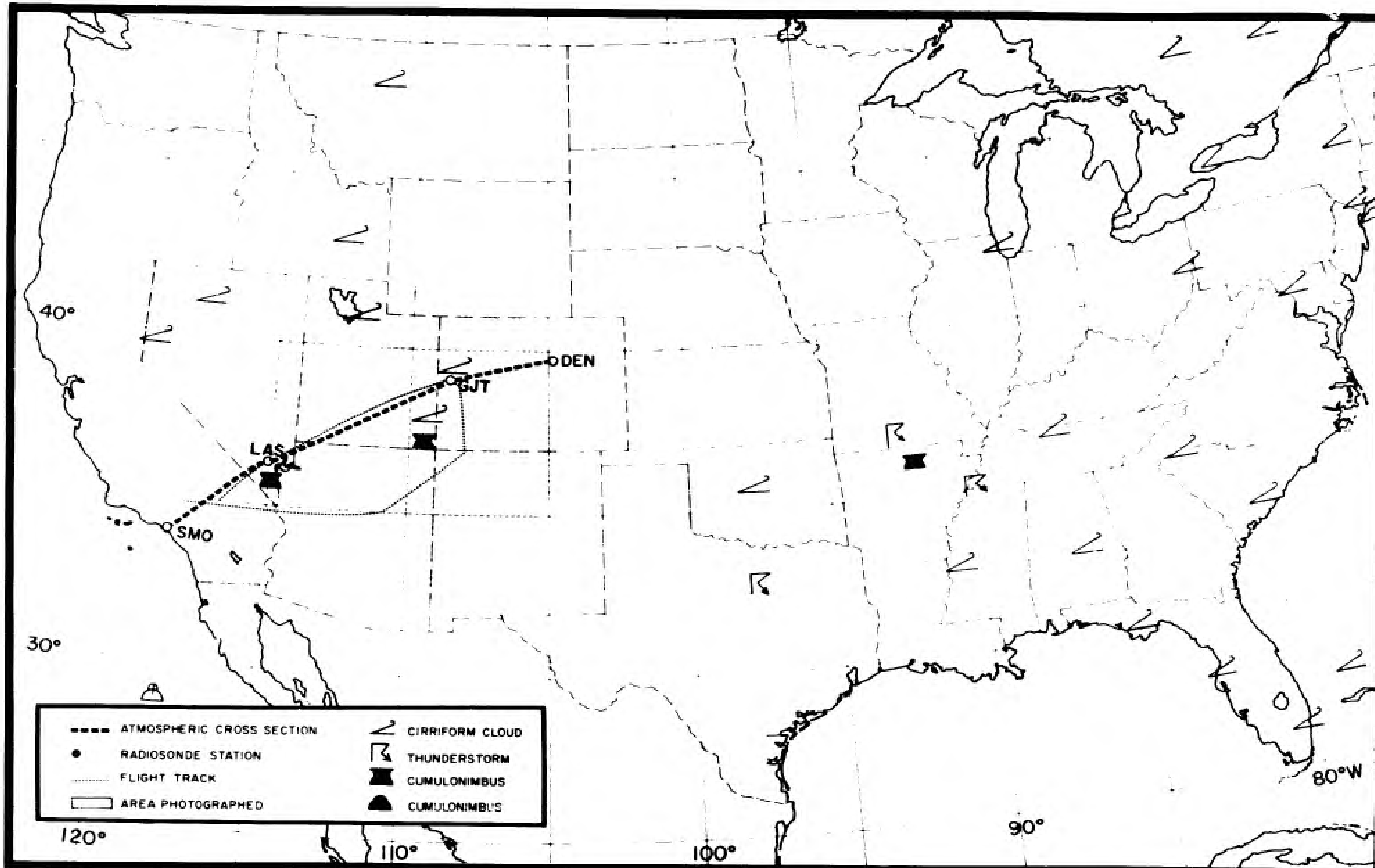

FIG. 5 AREA OF ANALYSIS RELATIVE TO LARGE-SCALE THUNDERSTORM DISTRIBUTION ON 29 APRIL 1960

the flight. This high-altitude cloud cover was associated with a frontal system over the Rocky Mountains.

2.3.2 Cloud Distribution

The only area that contained cloud cover in excess of 20,000 ft as determined from the 29 April U-2 photographs was in the vicinity of the Colorado-Utah border. Specifically, the flight track over the area of clouds above 20,000 ft was from Grand Junction, Colorado to Bryce Canyon, Utah. Figure 6 shows a profile of the clouds along this section of the flight track. The figure shows scattered areas of cloud with tops increasing from 23,500 ft near Grand Junction to 32,000 ft near 111°W. This trend in cloud top altitude along the flight track also shows at the level of cloud bases and closely parallels the changing height of the terrain. Again the profile does not show all the significant details of the cloud distributions, so a plan view of the cloud cover was constructed. Figure 7 shows the plan view of the cloud cover as photographed on the 29 April flight. This plan view shows all cloud cover over a 120-mile wide strip (60 miles either side of the flight track) between Grand Junction (GJT) and Bryce Canyon (BCE). Within this area, there were layers of clouds with tops at several different levels. The highest layer had tops around 32,000 ft. Other isolated tops of cumulonimbus also extend above the 30,000 ft level. A lower layer of cloud ranges in height from about 25,000 to 28,000 ft. Interspersed between portions of this layer tops between 20,000 and 28,000 ft were measured. Much of the rest of the area was covered with lower clouds (below 17,500 ft). Clear spaces within the area analyzed were very small and widely scattered over the area photographed.

2.3.3 Summary of 29 April Case Study

The U-2 photographs on 29 April showed cloud cover associated with a cold front that had become stationary over the Rocky Mountains. A very limited area of this frontal cloud cover exceeded altitudes of 20,000 ft. The cloud cover that did exceed 20,000 ft was confined to layers of higher clouds and isolated tops protruding above

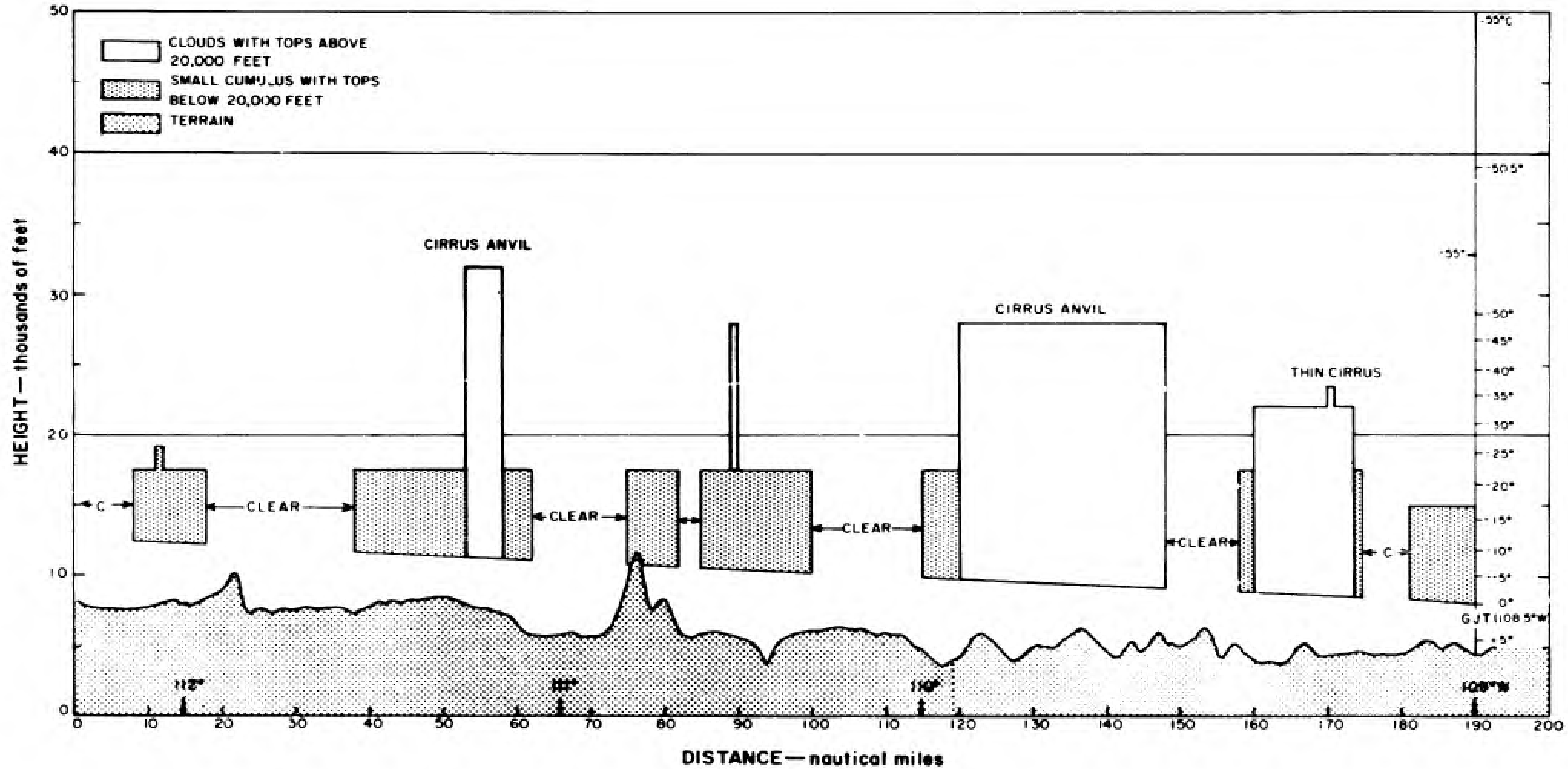

FIG. 6 PROFILES OF CLOUD COVER ON 29 APRIL 1960

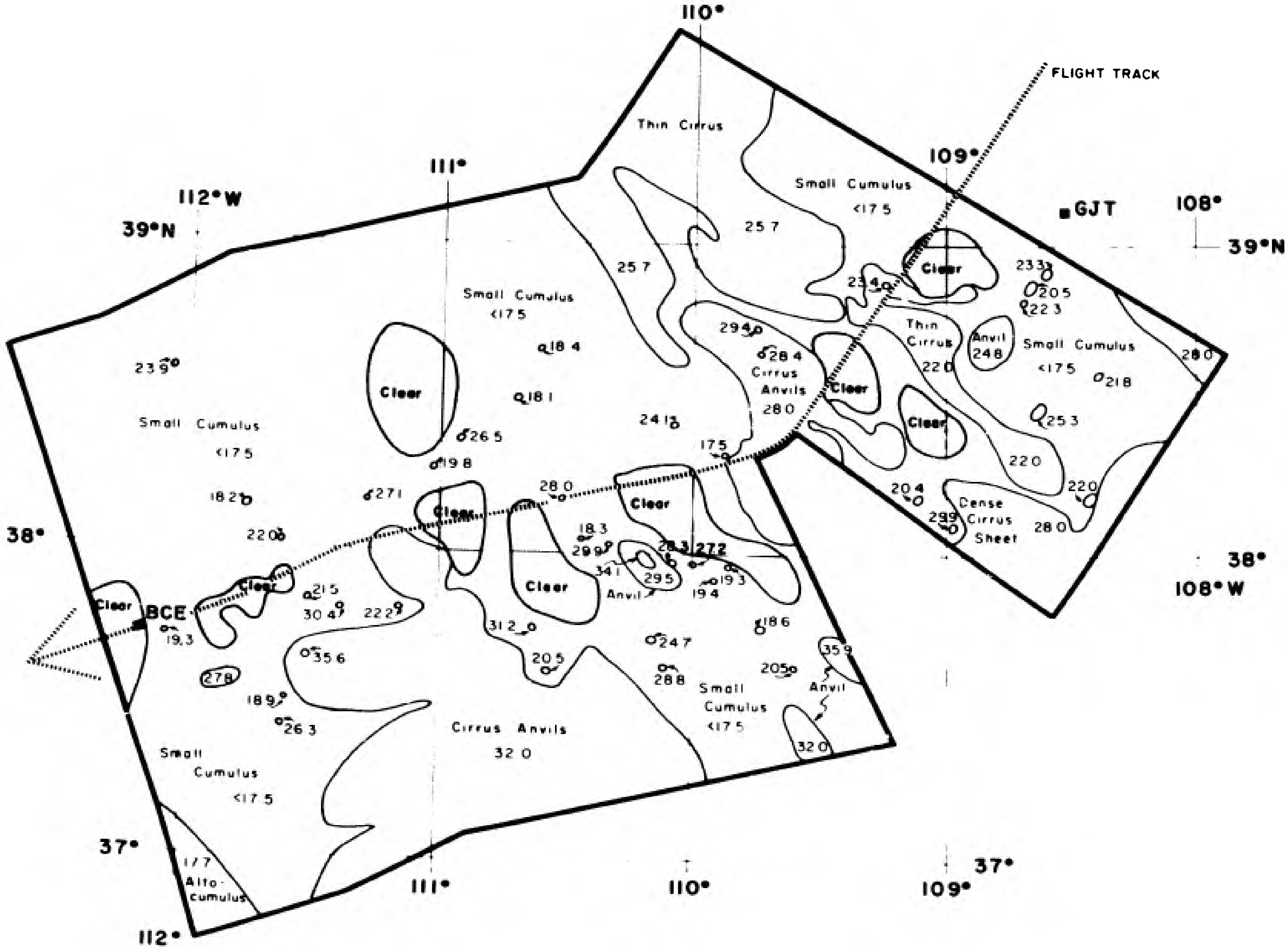

FIG. 7 PLAN VIEW OF CLOUD COVER ON 29 APRIL 1960

layers at altitudes below 17,500 ft. In this case the cloud-top altitudes appear to be related to the heights of the underlying terrain, i.e., the cloud base was at a constant level above the terrain and the cloud thicknesses were comparable over low and high terrain so the tops over the higher terrain were higher than the tops over the lower terrain. The maximum tops were close to the tropopause level and there was apparently no penetration of the tropopause by the tops of the thunderstorms. This is probably typical of cases when the convection is not strongly driven by intense surface heating of a tropical air mass.

3. SUMMARY AND CONCLUSIONS

3.1 SUMMARY

Three extended U-2 flights were examined to determine areas of cloud cover in excess of 20,000 ft. The three cases examined were 5 August 1960 (presented in Technical Note 64-1), 31 May 1962, and 29 April 1960. (The latter two cases are presented in this Final Report.) The object of these studies was to determine the dimensions and distributions of cloud cover at high altitudes and the meteorological conditions associated with the high altitude clouds. The three cases studied show four categories of high-altitude cloud cover. The 5 August case showed air mass clouds over the maritime areas of southeast United States and also over arid regions of southwest United States. The two cases presented in this Final Report discuss cloud cover with a squall line and with a frontal system. Methods of photogrammetrically analyzing the cloud cover were applied to the U-2 photographs to determine the location and altitude of cloud elements shown by the photographs from the three flights. Although it was originally planned to present profiles of cloud-top altitudes along selected lines, it was felt after the first case was concluded that profiles did not supply adequate information on cloud distributions. Therefore, the latter two cases were analyzed in greater detail and plan views constructed showing the distributions and altitudes of all clouds above 20,000 ft within 60 miles of the flight track.

3.2 CONCLUSIONS

The studies of high-altitude cloud cover in this investigation covered several types of atmospheric conditions, i.e., air mass clouds, squall line clouds, and frontal clouds. It was found that air mass convective activity that persisted for long periods (over southeastern United States) caused cirrus clouds up to the tropopause level while individual convective turrets protruded some 10,000 ft above the tropopause. Over the southwestern United States, the air mass cloud cover was more strongly driven by the solar cycle and the diurnal variability of cloud development did not permit adequate moisture to be injected to high levels to support visible cloudiness up to the tropopause level. The squall line cloud cover showed a tendency for higher isolated convective towers to be located at the south end of the squall line while toward the north where more widespread convective activity was occurring an extensive cirrus layer was measured at 32,500 ft (about 7,000 ft below the tropopause). Further northwest, a cirrus layer at the tropopause level was measured. Radar observations of air mass thunderstorms indicated that individual cells outside the area of the squall lines penetrated the tropopause by as much as 15,000 ft. These radar observations are in agreement with the 5 August 1960 case where it was found that, within the tropical air mass, the thunderstorm tops penetrated well above the tropopause.

The frontal cloud cover on 29 April 1960 was confined to an isolated area within a sharp upper air trough over Utah and Colorado. The tops of clouds in this area did not penetrate the tropopause, but the tops of the higher layers were very close to the tropopause level.

Based on these measurements of cloud cover over four different areas, one can conclude that the upper limit of layer clouds is the tropopause but clouds are not likely to reach this level until there has been continuous convective activity in the area for a period exceeding 24 hours, i.e., convective activity does not cease at night.

The individual convective towers may penetrate the tropopause by as much as 10,000 to 15,000 ft when the convective activity is occurring within moist tropical air masses. The taller convective towers appear to be arranged in clusters. Between the clusters, the cloud-top altitudes are much lower. The number of tops within clusters and the spacing of clusters has not been determined, but is probably continually changing, especially in the early stages of development. The anvils from individual towers in a cluster merge to form an extensive cirrus sheet that eventually extends 60 to 100 or more miles downwind from the cluster. Apparently in later stages of development the cirrus sheets from several clusters merge to form an extensive, smooth cloud deck. These clusters of cumulonimbus are what one sees in meteorological satellite photographs; in such photographs individual turrets in the cluster are not identifiable.

4. RECOMMENDATIONS FOR FUTURE RESEARCH

Knowledge of the upper structure of cloud cover is limited, primarily because of the lack of observations from above the clouds. Since the late 1950's, U-2 photographs have provided records of the appearance of cloud cover from altitudes in excess of all but the very highest clouds. Such photographic records, when properly analyzed, should provide basic knowledge of the topography of cloud cover just as aerial photographs have been analyzed to provide knowledge of the topography of the earth's surface. Unlike the earth's surface, however, the cloud cover changes rapidly, and a map of the cloud cover at a given instant would not be the same as a map a short time later. It is necessary therefore to make many maps of cloud cover over many times of day and times of year, and at various geographical locations to provide the fundamental topography of clouds that might exist over a hemisphere under a specified distribution of synoptic and/or air mass conditions. This knowledge would provide a sound basis on which to construct cloud models that would eventually form part of any computer-activated program in which cloud distribution is a parameter. This final report, together with Technical Report 1 on this contract, provides much useful information of a type that exists in extremely limited quantity. The techniques developed during the project have greatly advanced the methods for analysis of U-2 film and will be of interest to all other organizations possessing such film.

Future work with U-2 film should be aimed toward determination of the percentage of cloud cover at various altitudes when the surface observer reports a given percent of cloud cover at the level of the cloud bases. Such determinations would be a logical continuation of studies[5] that specify the contribution of clouds of various sizes to the total amount of cloud cover. To specify the coverage at various altitudes would virtually imply a contour map on which each individual cloud would have contours drawn around it at appropriate intervals. Such a map is not impossible if the techniques applied to terrain mapping are applied to the cloud elements. Additional studies in comparisons between radar data and cloud cover are also required. The radar data that should be considered are radarscope photographs supplemented with measurements of heights of echo tops. The use of these data would make it possible to assess the stage of development of a specific cloud. The radar data, together with hourly surface observations of clouds, would make it possible to determine the rapidity with which convective cloud cover develops. There is evidence that clouds may develop and grow to altitudes of 60,000 ft in less than 1-1/2 hours.

Finally, studies should be made of the importance of roughness or nonuniformity of the upper surface of the cloud cover especially when there are extensive areas of clouds. Specifically, the size, vertical extent, and spacing of protuberances that are significant when one examines the clouds at various wavelengths of the electromagnetic spectrum must be determined.

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APPENDIX

SUPPORTING METEOROLOGICAL DATA

A-1 METEOROLOGICAL CHARTS FOR 31 MAY 1962 CASE

A-1.1 Surface and Upper Air Charts

The surface weather chart (Fig. A-1) shows a low pressure area centered near the southern tip of James Bay. A cold front extends southwestward from the low through Kansas thence in a northerly direction into Montana. Numerous thunderstorms were occurring with the portion of the front between the low center and Colorado. Within the tropical air mass south and east of the cold front squall line thunderstorms were commonplace, as indicated by the four squall lines shown on Fig. A-1. The squall line over Texas was the one photographed by the U-2.

Temperature and dew point values indicated on the chart show that over most of the area where squall lines were occurring temperatures were near 80°F and dew points were between 60 and 70°F. In the vicinity of the Texas squall line the temperature was over 90°F and dew points just behind the squall line were as low as 10°F. Such large discontinuities in dew point are quite common over Western Texas and the line along which the discontinuities occur has been termed the "Texas dew-point front."

At the 700-mb level (approximately 10,000 ft above sea level) a trough is located over the Great Lakes and a closed low appears over New Mexico and Colorado. (See Fig. A-2.) Temperatures at this level range from -5°C over Canada to 10°C over Texas and Mexico and parts of Arizona. Moisture on this chart is indicated by the dew-point depression--the difference between actual air temperature and the temperature to which the air must be cooled to become saturated. Analyzed values of dew-point depression show a general pattern of moist air

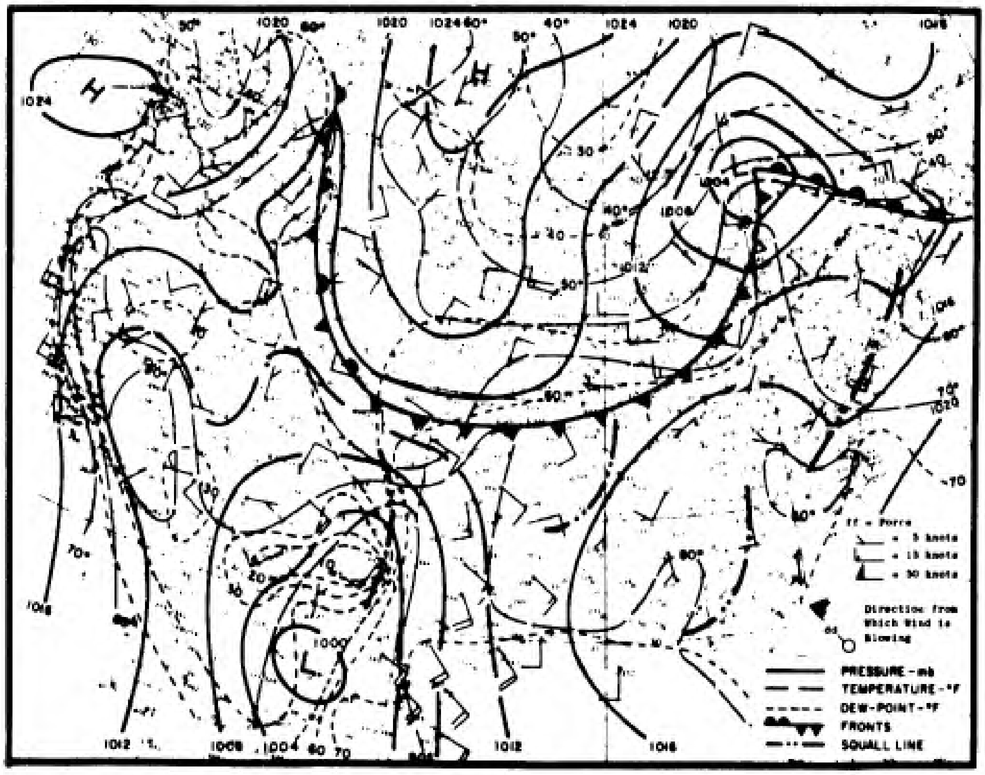


FIG. A-1 SURFACE WEATHER CHART, 0000 GMT, 1 JUNE 1962

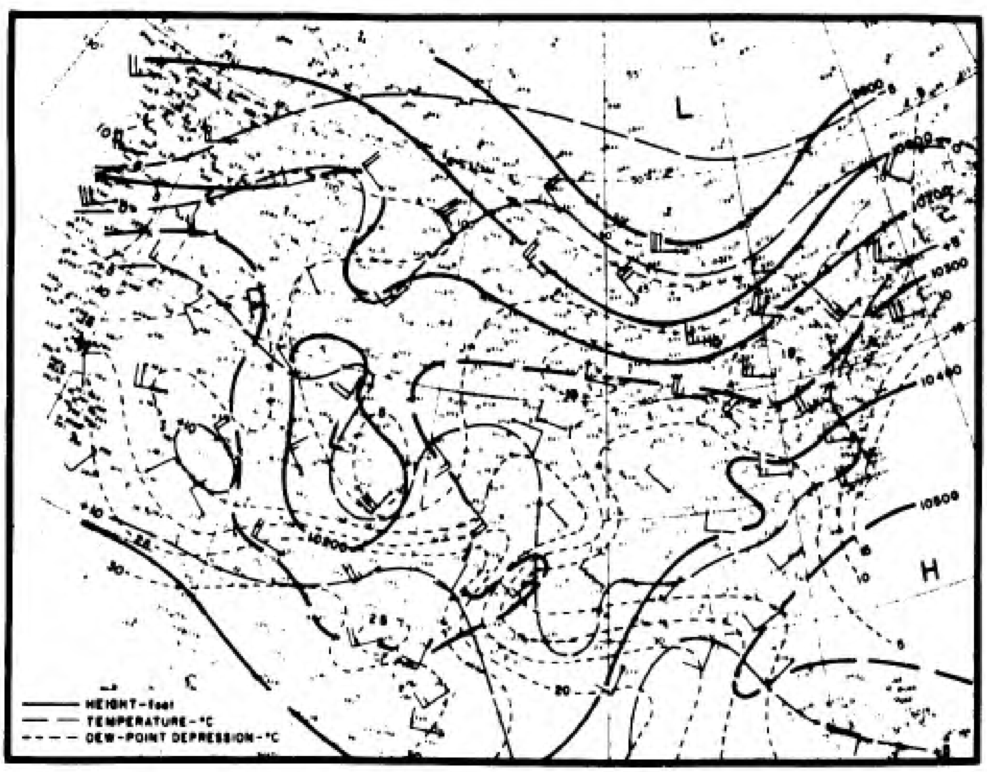


FIG. A-2 700-mb CHART, 0000 GMT, 1 JUNE 1962 extending from South Carolina generally westnorthwestward to Oregon. South of this general area the air becomes much drier with dew-point depressions of 30°C along the Mexican border. To the north, dry areas are evident over western Pennsylvania and Eastern Iowa. Further north moist air is indicated by the dew-point depression of 5°C or less over New England and the northern Great Lakes.

Figure A-3 shows temperature, moisture and wind at the 500-mb level (approximately 19,000 ft). At this level the trough over the Great Lakes and the closed low over the Texas-New Mexico border are apparent. Temperatures at this level range from -10°C over the southern part of the country to -25°C over the Pacific northwest. Two areas of moist air are evident (from dew-point depressions less than 5°C). These are located over southern Florida and over eastern Colorado and portions of the neighboring states. An area of quite dry air extends from southwestern Canada southwestward across Illinois into the area of the Ohio River Valley. Dry air also covers the area of southwestern United States along the Mexican Border.

Figure A-4 shows temperature and winds at the 300-mb level (approximately 31,000 ft) no moisture analysis is shown on the map because only the stations with temperatures warmer than -40°C reported relative humidity. The -40°C isotherm on the figure dips southwestward from Maine to Texas thence runs westward to southern California. Winds at the 300-mb level are generally stronger than at the lower levels. An area of winds in excess of 50 knots is located over southern Texas and Arizona Also along northern United States there are intermittent reports of strong winds.

Figure A-5 shows conditions at the 100-mb level (approximately 54,000 ft). Temperatures at this level range from -50°C over the Pacific Northwest to -70°C over southern Texas. Winds at this level are relatively light and blow generally from a westerly direction except in the vicinity of the small highs and lows.

Figure A-6 shows the height and temperature of the tropopause. The contour lines show that the tropopause height ranges from

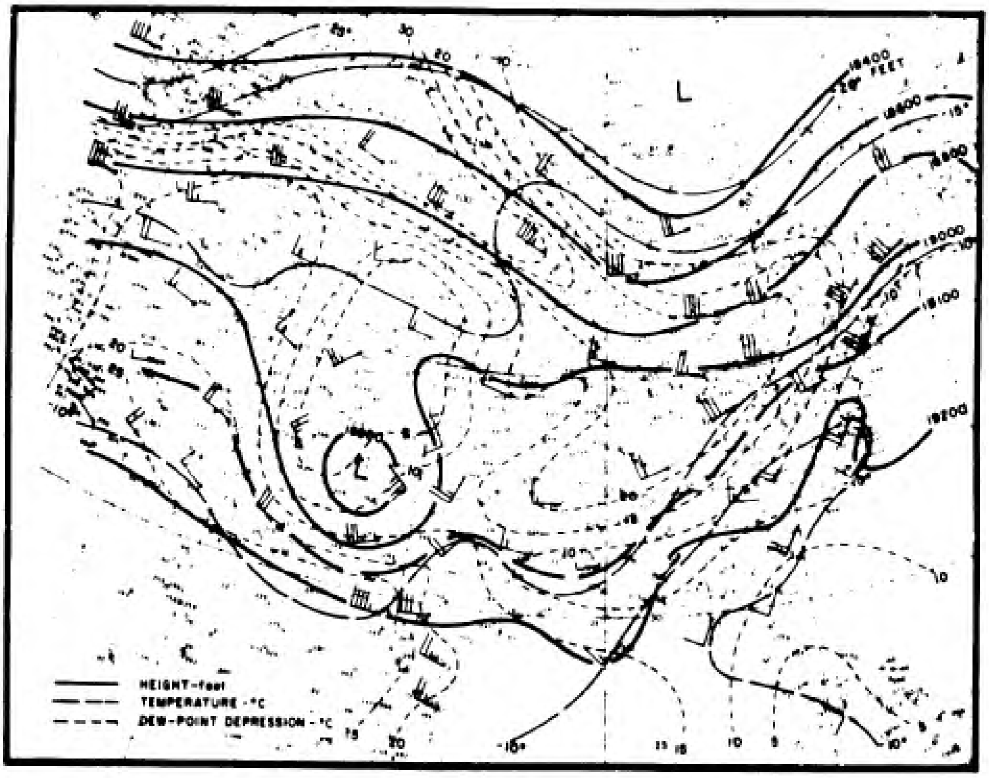


FIG. A-3 500-mb CHART, 0000 GMT, 1 JUNE 1962

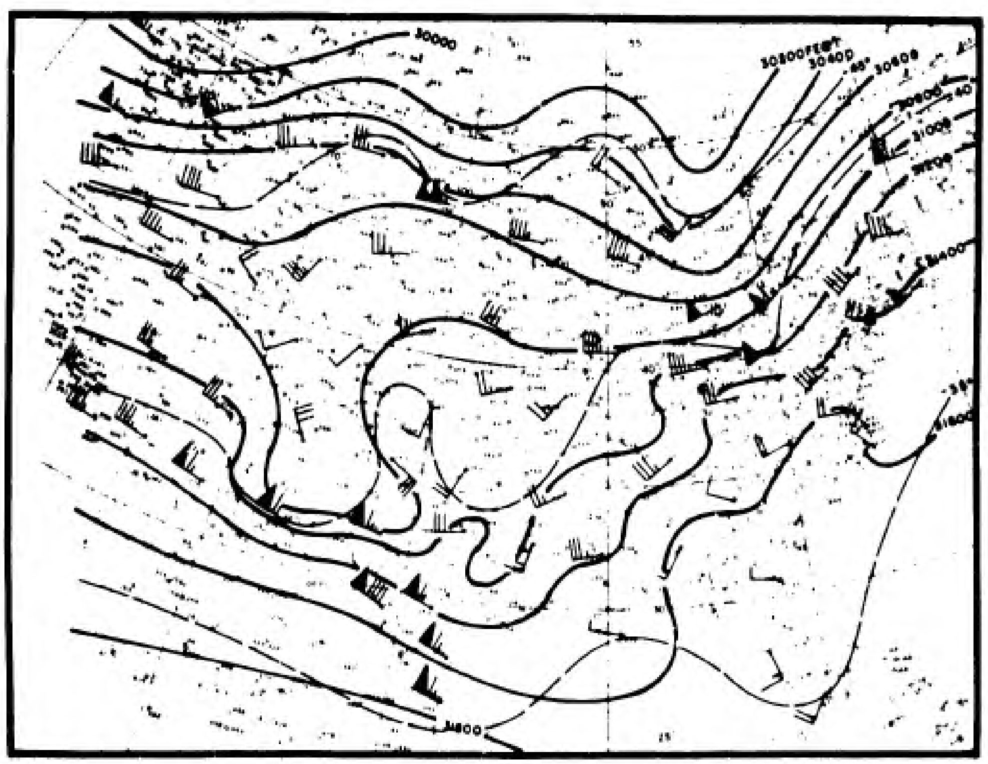


FIG. A-4 300-mb CHART, 0000 GMT, 1 JUNE 1962

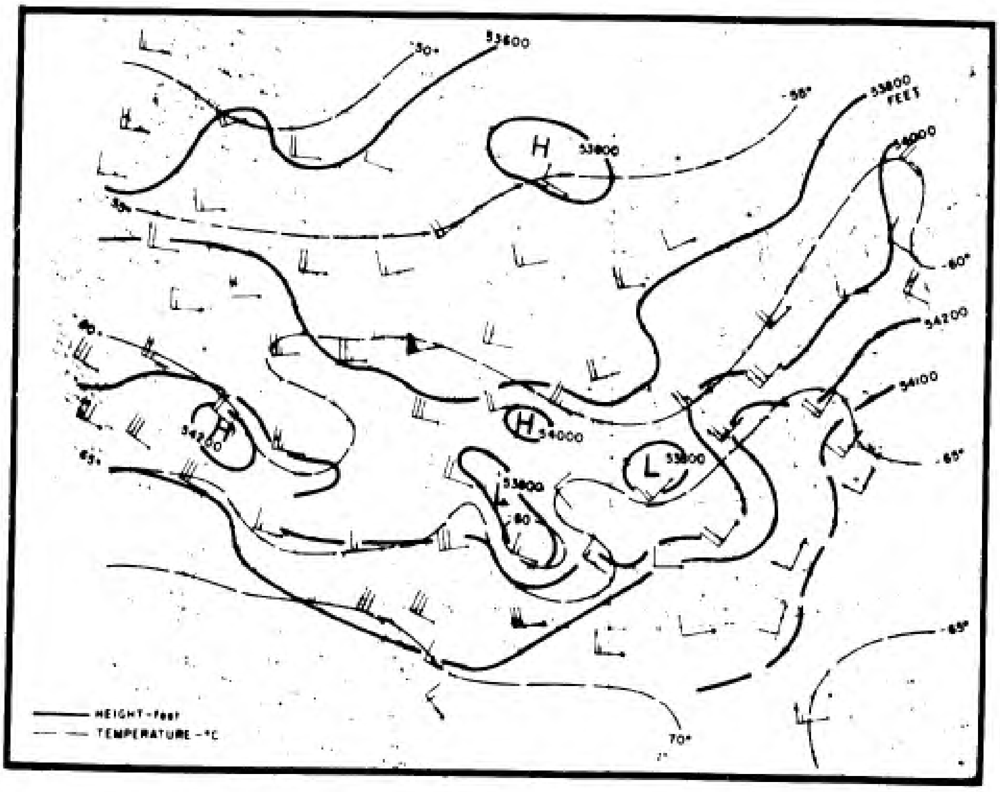


FIG. A-5 100-mb CHART, 0000 GMT, 1 JUNE 1962

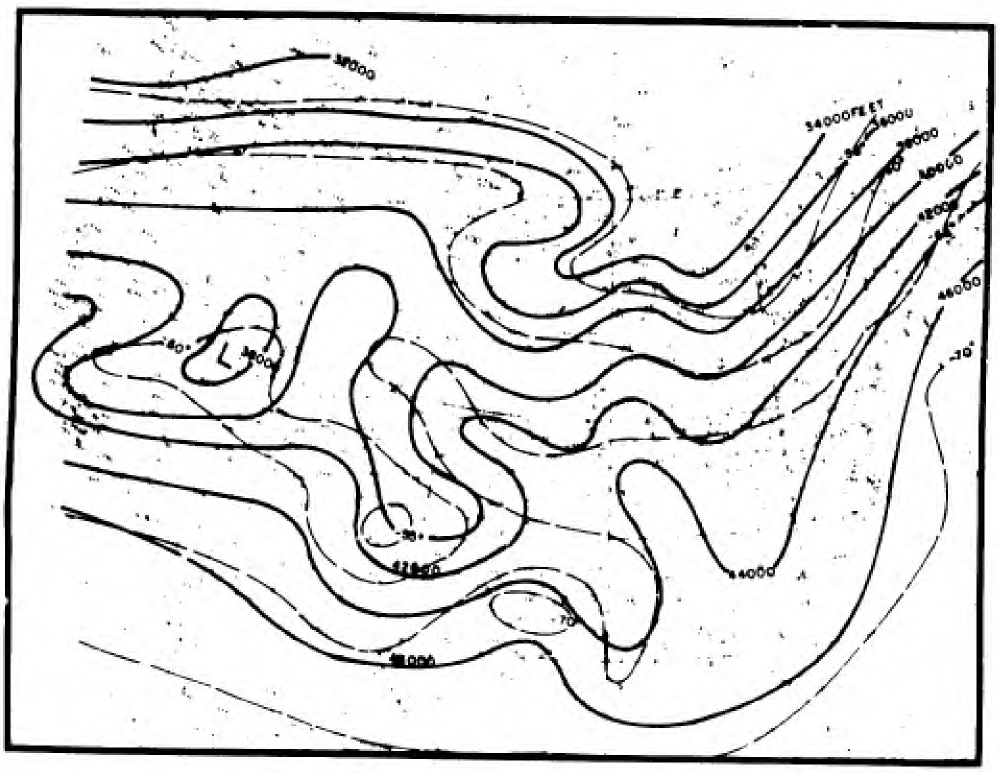


FIG. A-6 TROPOPAUSE CHART, 0000 GMT, 1 JUNE 1962 close to 34,000 ft over northern U.S. to 46,000 ft over southern United States. Superimposed on this gradual upward slope are east-west variations or perturbations. Temperature variations over small distances are also apparent, e.g., -55°C over northern Texas contrasted with -70°C over the Texas-Louisiana border.

A-1.2 Cross Sections

Three north-south sections are shown in Fig. A-7. These cross sections show the distribution in the vertical of temperature, moisture and wind All three cross sections show the north-south variability in wind speed. The greatest variability appears in Fig. A-7(a) where the wind just above the 300-mb level was 3 knots at Denver as compared with 90 knots at El Paso In Fig. A-7(b) the northernmost station (north Platte) has strong winds at the 100- and 200-mb level, but at the other levels the tendency for strongest winds to the south is apparent. The low-pressure area west of Amarillo is apparent from the southeasterly winds above the 700-mb level at that station. Also of interest at Amarillo is the dome of cold air caused by downdrafts within the area of thunderstorms The isotherms show that the air in this cold dome is as much as 10° colder than the air at the same level at Midland. It is interesting to note that the level of the reported cloud bases at Amarillo was 10,000 ft or more above the terrain during the afternoon and evening. During the same period nearly all the stations around Amarillo reported clouds at much lower levels even down to 1500 to 2000 ft. Moisture adequate for cloud cover is contained within the dome as indicated by dew-point depressions less than 5°C. The reason for the absence of clouds below 10,000 ft at Amarillo therefore remains a mystery.

The moisture pattern shown by the cross sections increases in complexity from west to east. In Fig. A-7(a) there is a considerable gradual decrease in moisture from north to south In Fig A-7(b) the moist tongue extends to higher altitudes at Dodge City than at stations to the north or south and to a lower altitude at Amarillo than to the north or south Any general pattern of north-to-south decrease in

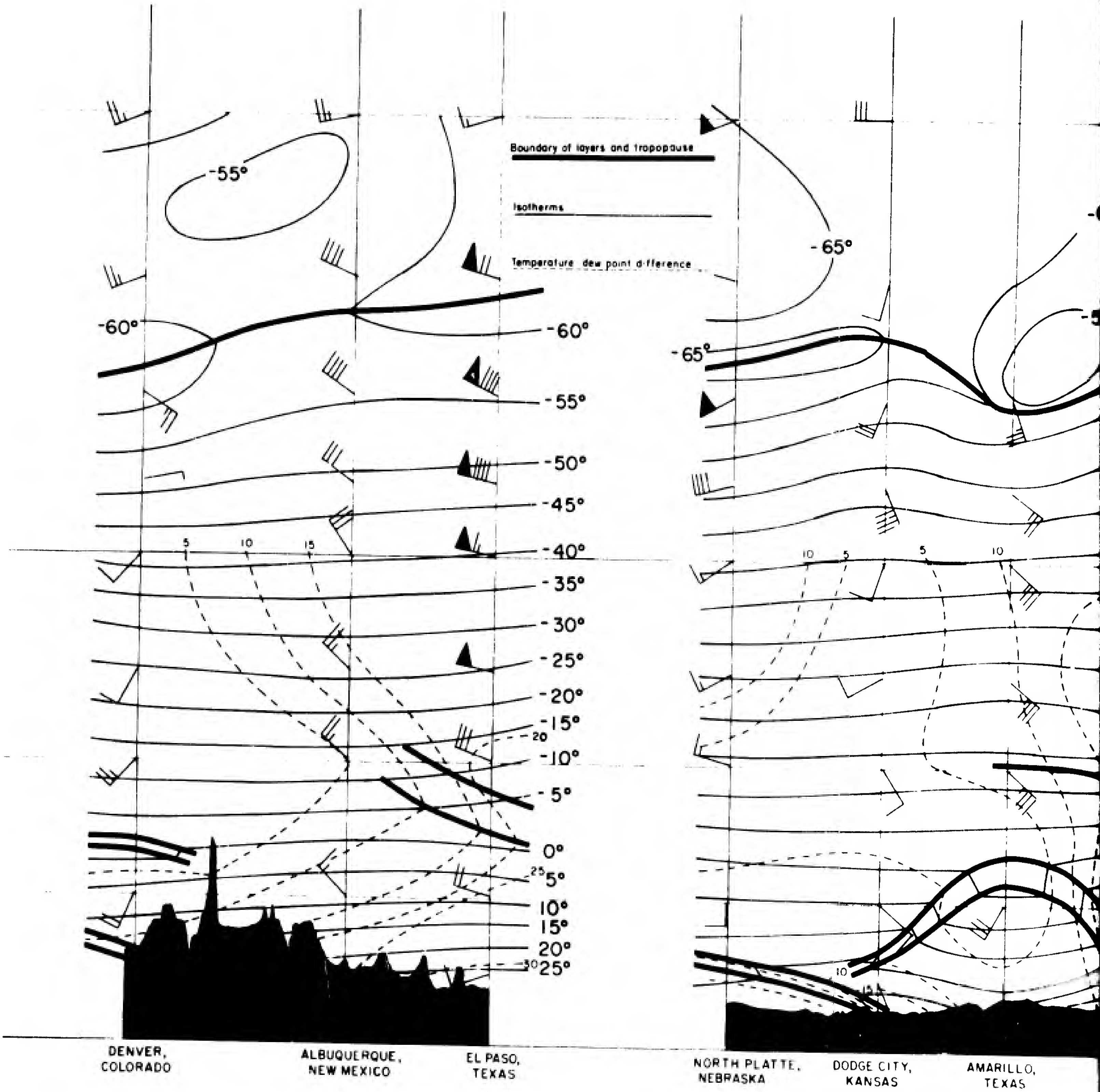
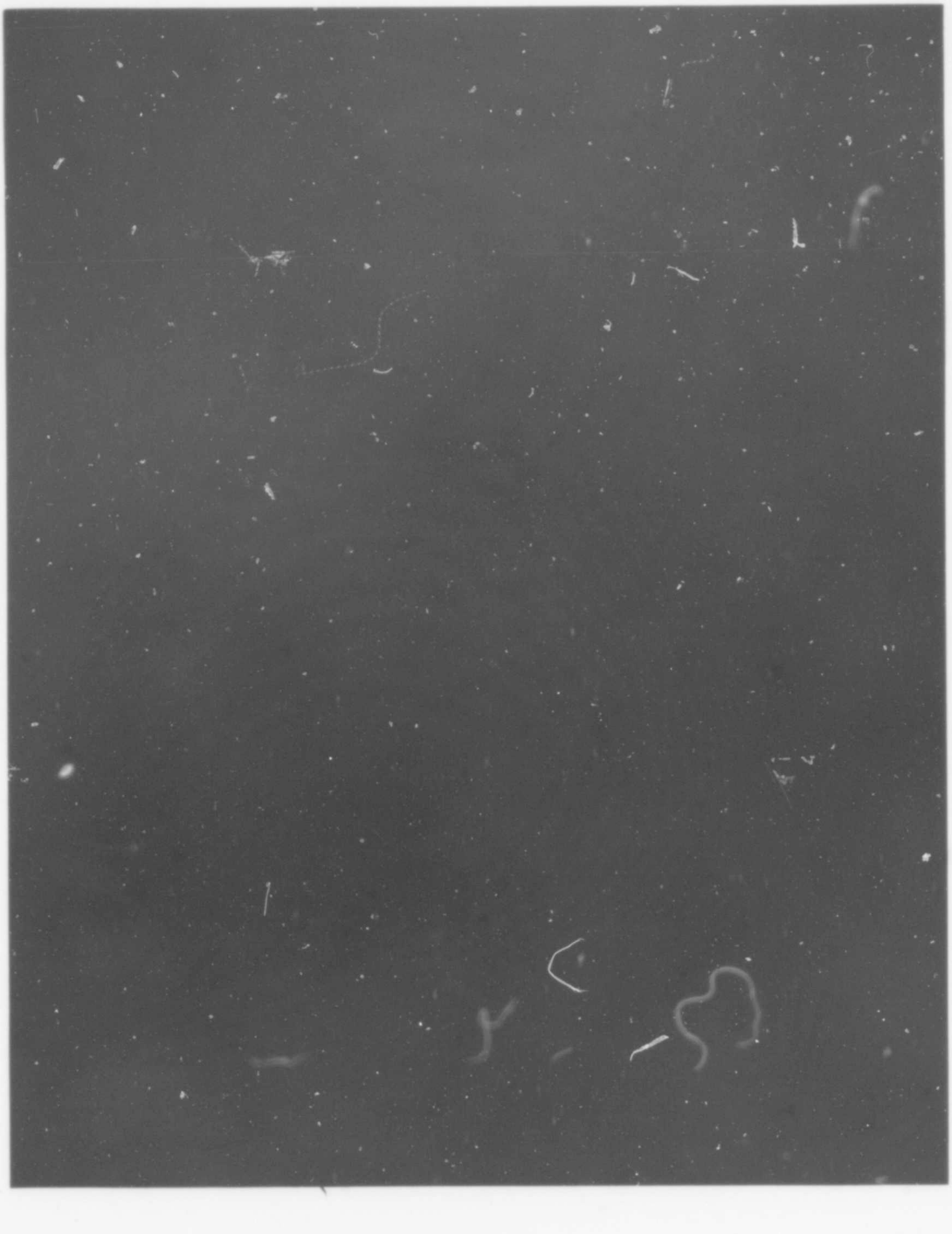
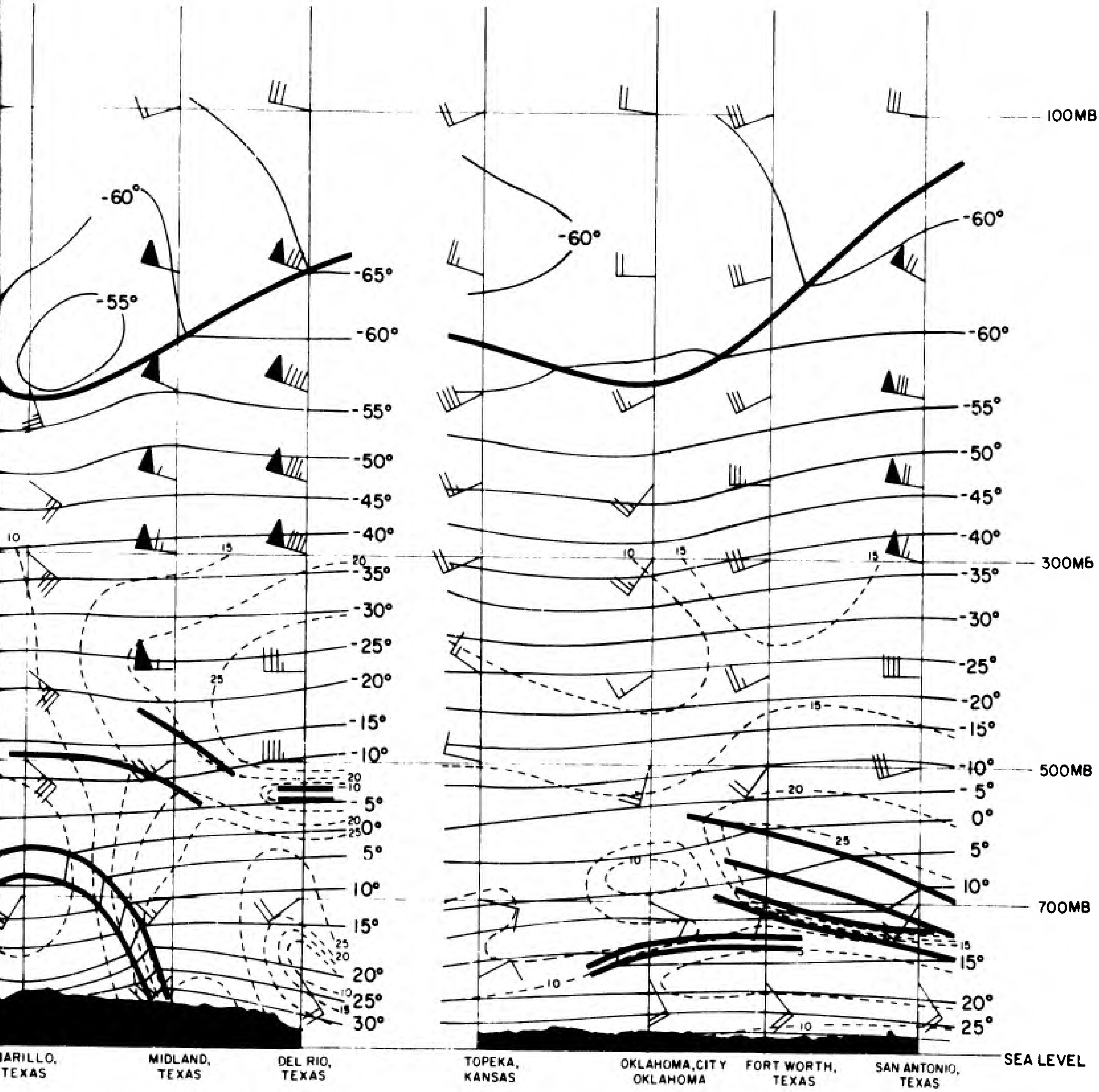


FIG. A-7 ATMOSPHERIC CROSS SECTIONS

A





OSS SECTIONS, 0000 GMT, 1 JUNE 1962

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moisture is further complicated by the moist layer just below the 500-mb level at Del Rio. In Fig A-7(c) the moisture tends to be stratified with the driest stratum above the 700-mb level located south of the moist stratum. Below the 700-mb level, a moist layer is shown by the 5° dew-point depressions over the south end of the cross section.

A-1.3 Hourly Cloud and Weather Observations

Cloud and weather observations taken each hour by surface observers within and adjacent to the area of the squall line were analyzed. The analyses are presented as a series of nephanalyses in Fig. A-8. The figure shows that, at 2100 GMT, thunderstorm activity was reported at several locations to the east and south of the extensive area over Colorado and adjacent Kansas. By 1900 GMT, the major area of thunderstorms had spread to the south while the isolated areas increased in size. At 2300 GMT, the pattern was quite similar to that at 2200 GMT except that only a single band of thunderstorms extended southward through western Texas. Considerable new development of thunderstorms apparently took place between 2300 GMT and 2400 GMT since, at the latter time, the previously isolated areas had merged to form a continuous area of thunderstorms. Between 2400 GMT and 0100 GMT additional development apparently took place, primarily in extreme northern Texas. Also by 0100 GMT, the cirrus clouds were more widely observed so that the tongue of no high-altitude clouds that previously (at 2300 GMT) extended from Texas into southern Oklahoma greatly decreased in size.

A-1.4 Hourly Radar Summaries

Available summaries of radar data for a brief period during the history of the squall line are presented in Fig. A-9. These summaries do not give the locations of individual echoes, except for some isolated cells or significant echoes (because of great height or strong intensity) within areas of widespread activity. Instead the boundaries of the echo area are given along with the character, intensity, and tendency of the echo area. The figure shows a number of areas of echo scattered over the midwest. At the northern edge of the area shown by the maps, the

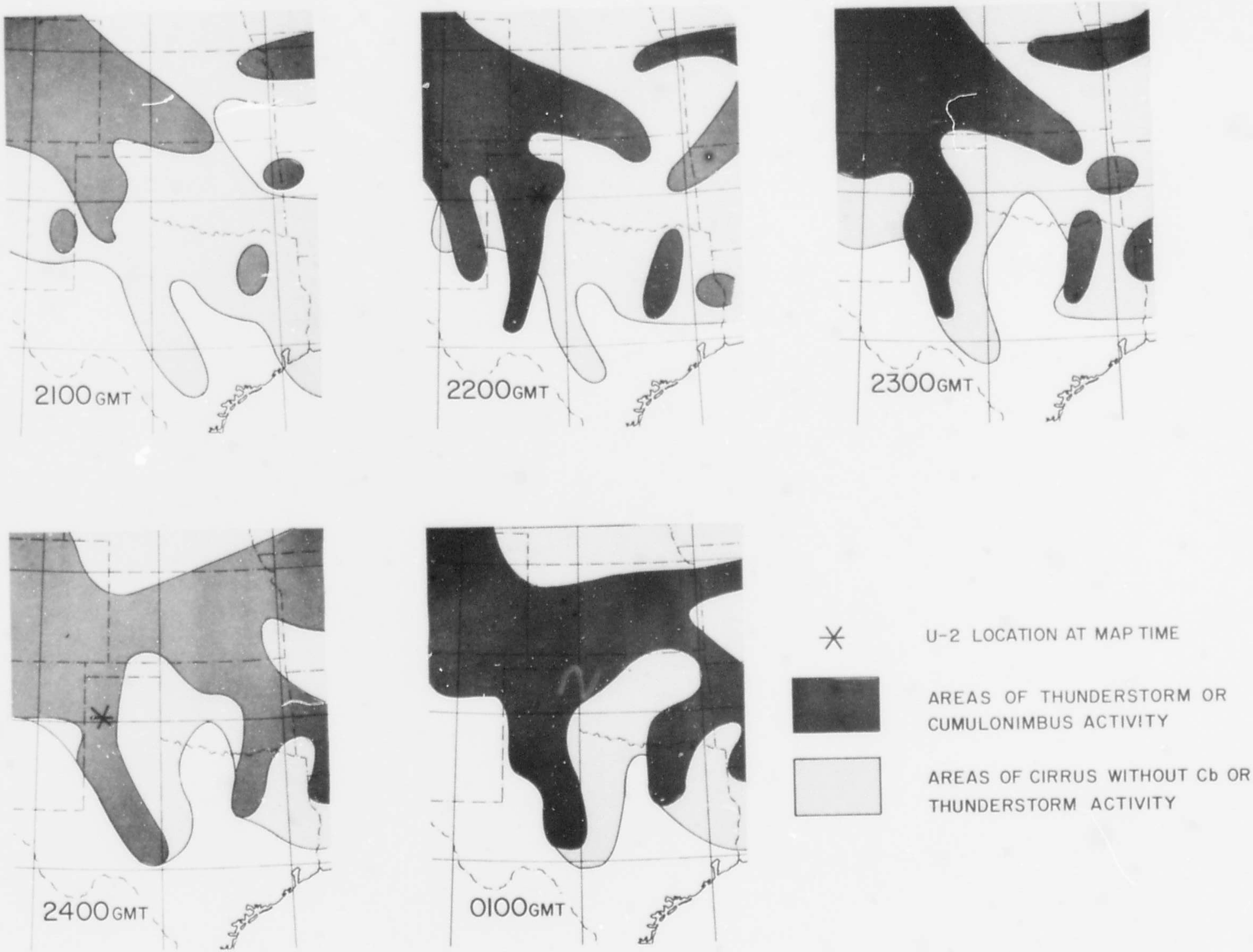

FIG. A-8 HOURLY NEPHANALYSES OF CLOUD COVER FOR 31 MAY 1962 CASE STUDY

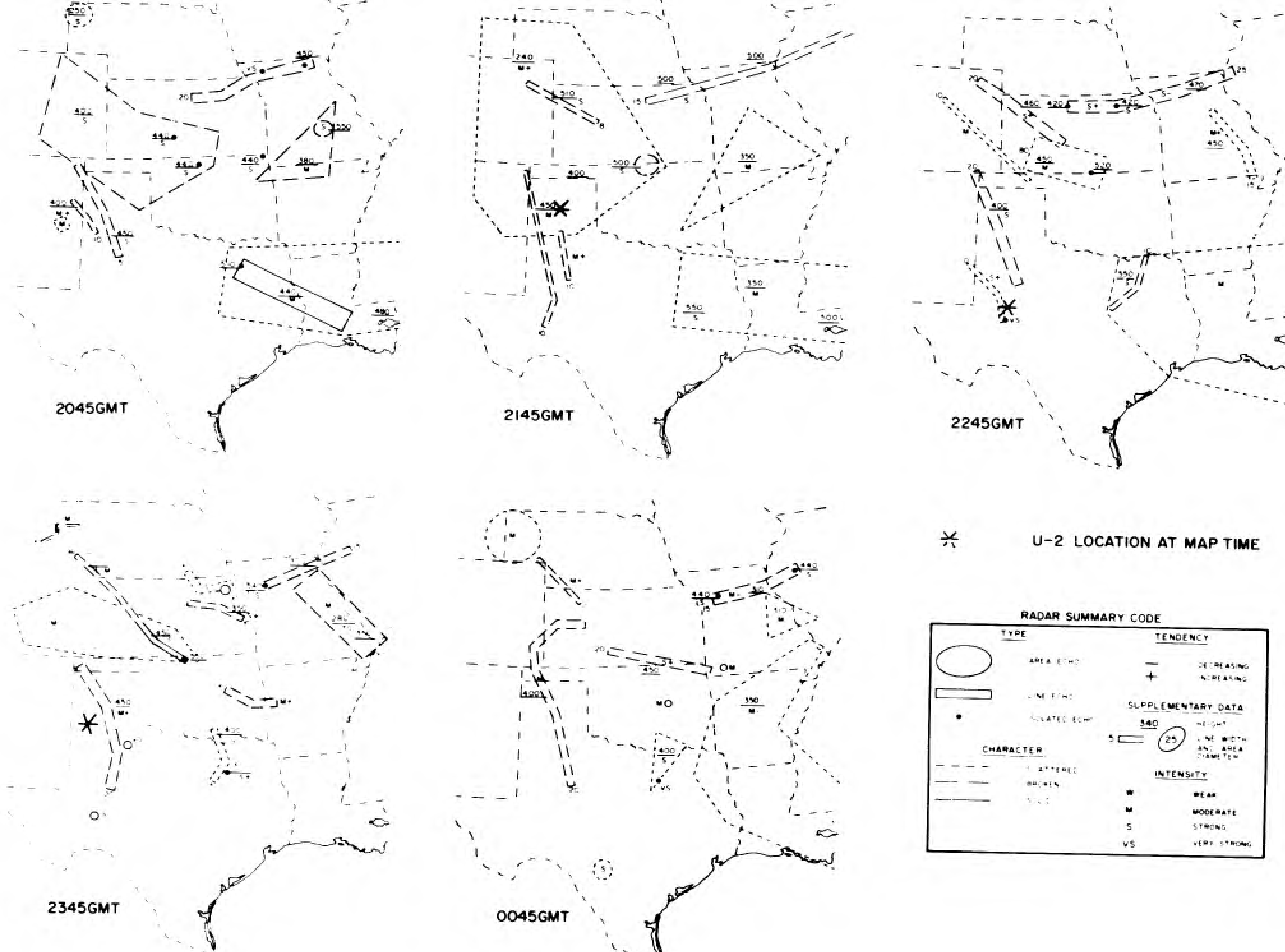

FIG. A-9 HOURLY RADAR SUMMARIES

activity associated with the cold front is shown by an east-west band. This band is best defined at 2145 and 2245 GMT. The squall line appeared to the radar as elongated bands of echoes extending southward from a large area of echo into northern Texas. Examination of these bands at hourly intervals shows a continually-changing pattern. At the time of the first three charts, the squall line consists of two bands of echo with tops in the vicinity of 45,000 ft. At the last two hours there is only a single band of echo and the tops are still 45,000 ft or less.

Other areas of echo contain tops higher than those in the squall line. For example tops between 50,000 and 55,000 ft are reported over eastern Texas, Missouri, Kansas, and northern Oklahoma. Comparison of echo heights at 2345 with tropopause heights at 2400 (Fig. A-6) shows that tropopause heights are considerably lower than the echo tops. The tropopause heights range from 40,000 to 46,000 ft in areas of tops up to 55,000 ft, implying that some cells are penetrating some 15,000 ft through the tropopause.

A-2 METEOROLOGICAL CHARTS FOR 29 APRIL 1960 CASE STUDY

A-2.1 Surface and Upper Air Charts

Figure A-10 shows the sea level pressure pattern, frontal positions and analyses of surface temperature and dew point at 0000 GMT on 30 April 1960 (about 1-1/2 hours after the termination of the flight).

The major features of the pressure pattern are the low-pressure areas in the Texas-Oklahoma region and the high-pressure center over Montana. The western boundary of the cold high-pressure area is indicated by the frontal line extending from New Mexico northwestward through Utah, Idaho, and Montana into Canada. Temperatures range from 31°F at Denver, Colorado on the cold side of the front to 73°F at Las Vegas, Nevada on the warm side of the front. The dew-point temperatures do not show as much variation across the front and tend to be in the 20's on the warm dry side; in the 30's on the cool moist side.

At the 700-mb level (Fig. A-11) a trough extends southwestward from Hudson Bay to southern California. The southwest portion of this trough thus lies very close to the flight track of the U-2. The

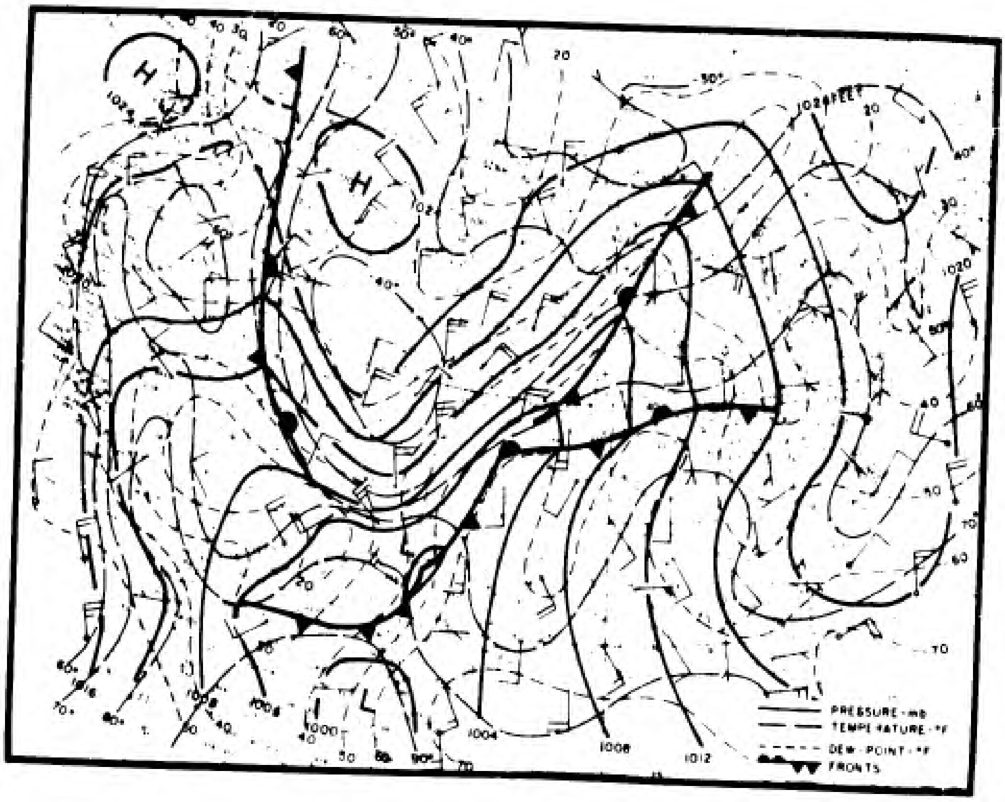

FIG. A-10 SURFACE WEATHER CHART, 0000 GMT, 30 APRIL 1960

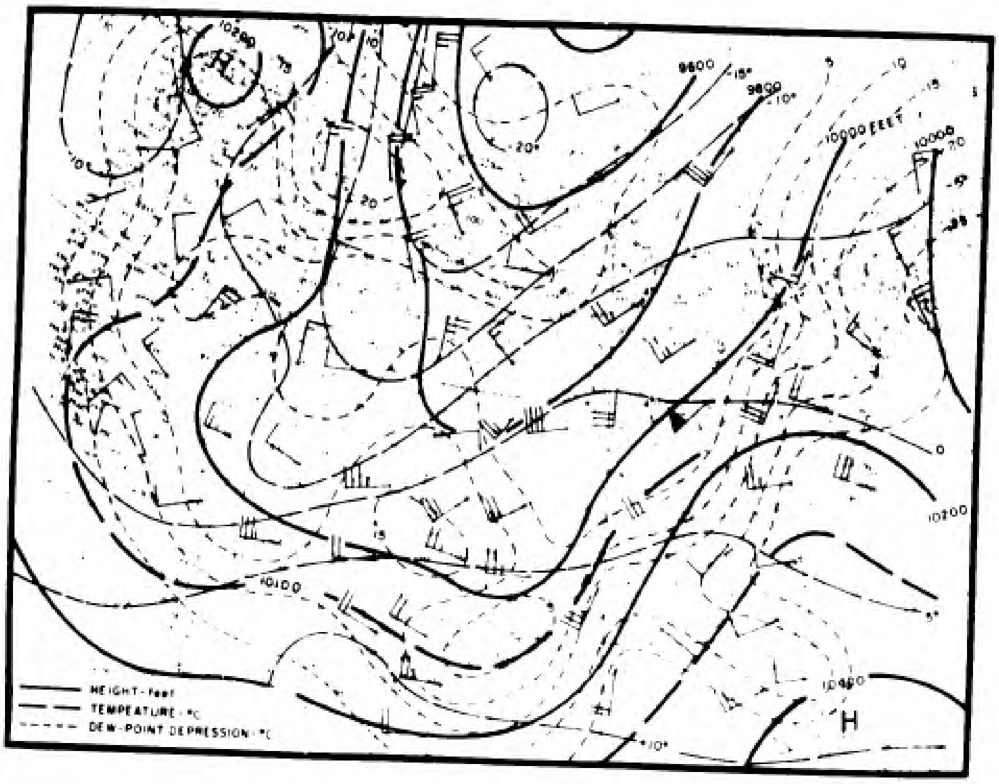

FIG. A-11 700-mb CHART, 0000 GMT, 30 APRIL 1960 analyses of dew-point depressions at this level show a moist region extending from Salt Lake to Indiana, thence northward to Hudson Bay. Much drier air is shown along the West Coast and over central Texas.

At the 500-mb level (Fig. A-12) the height and temperature pattern is much the same as at the 700-mb level. The moisture pattern is different however, in that the only area in the western states with dew-point depressions less than 5°C is in Colorado and Utah and lies right along the U-2 flight track.

At the 300-mb level (Fig. A-13) a closed low over Colorado is shown in the trough and the trough bulges westward into northern California. Winds in excess of 60 knots are indicated over much of the southwest and eastern half of the country. The notable exception is over Colorado and Utah, where winds of 10 knots or less were observed.

At the 100-mb level (Fig. A-14) the trough is much shallower over the southwestern states. In addition, the winds are more uniform than at the lower levels.

The height and temperature of the tropopause is shown by Fig. A-15. On this date there was a discontinuity in the tropopause (shown on the figure by a heavy line with dots). South of the discontinuity, the major tropopause was the high cold tropical tropopause, typically above 50,000 ft with temperatures below -60°C. To the north, the tropopause ranged from 30,000 to 40,000 ft and over the western states temperatures were -50° to -60°C. The discontinuity lies between Grand Junction, Colorado and Las Vegas, Nevada, perpendicular to the flight track.

A-2.2 Cross Sections

Figure A-16 shows a cross section along a line from Denver, Colorado to Santa Monica, California. Along the northeast end of this line the air was moist, as indicated by dew-point depression of less than 5°C. At the southwest end of the line, dew-point depressions fall to values exceeding 20°C just below the 500-mb level. The cross section shows the double tropopause that was discussed in connection with

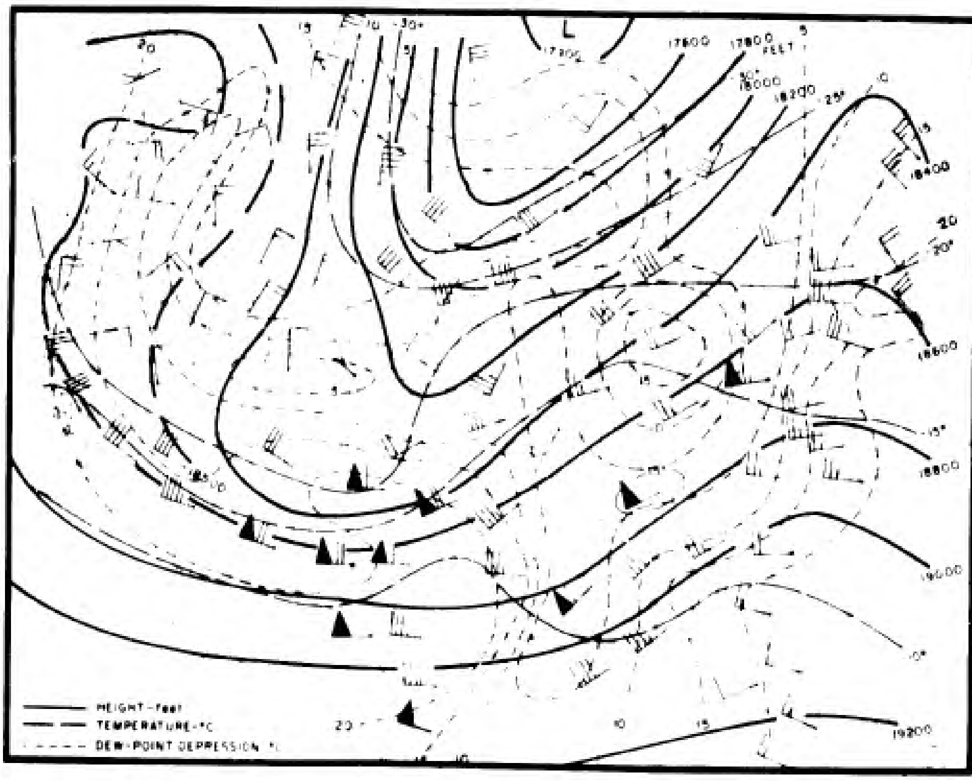

FIG. A-12 500-mb CHART, 0000 GMT, 30 APRIL 1960

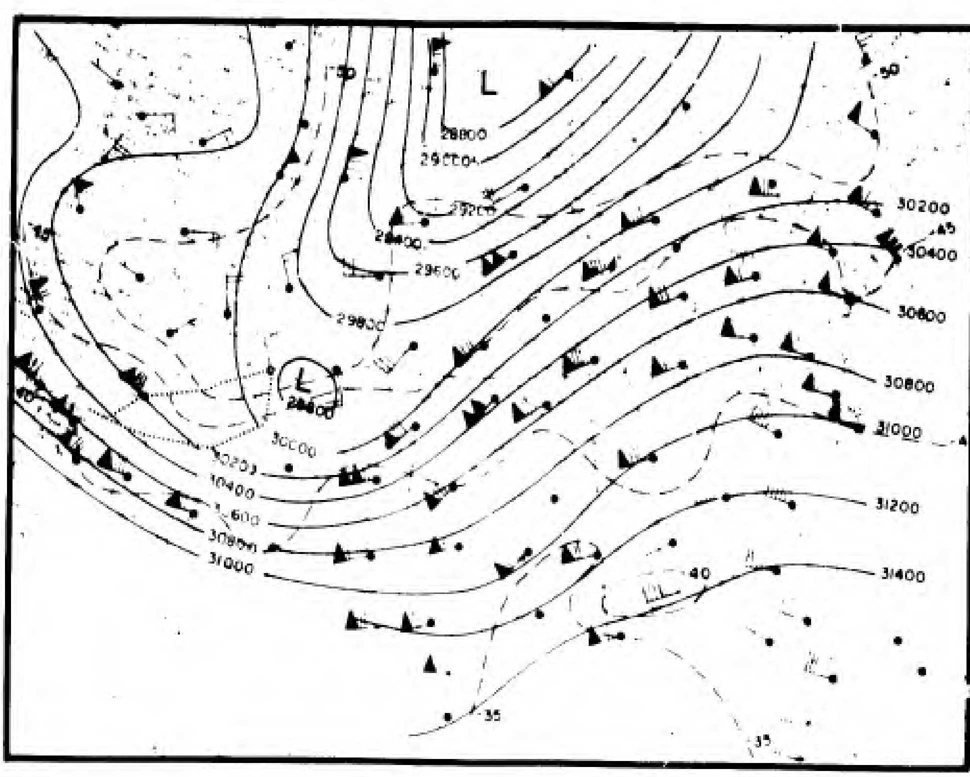

FIG. A-13 300-mb CHART, 0000 GMT, 30 APRIL 1960

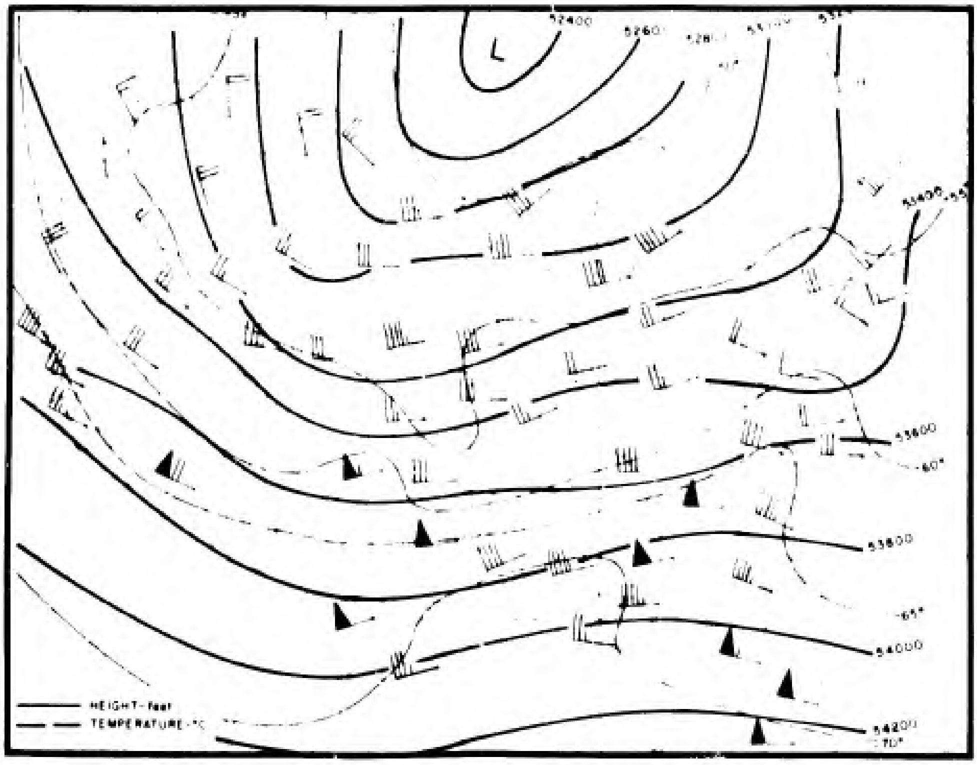

FIG. A-14 100-mb CHART, 0000 GMT, 30 APRIL 1960

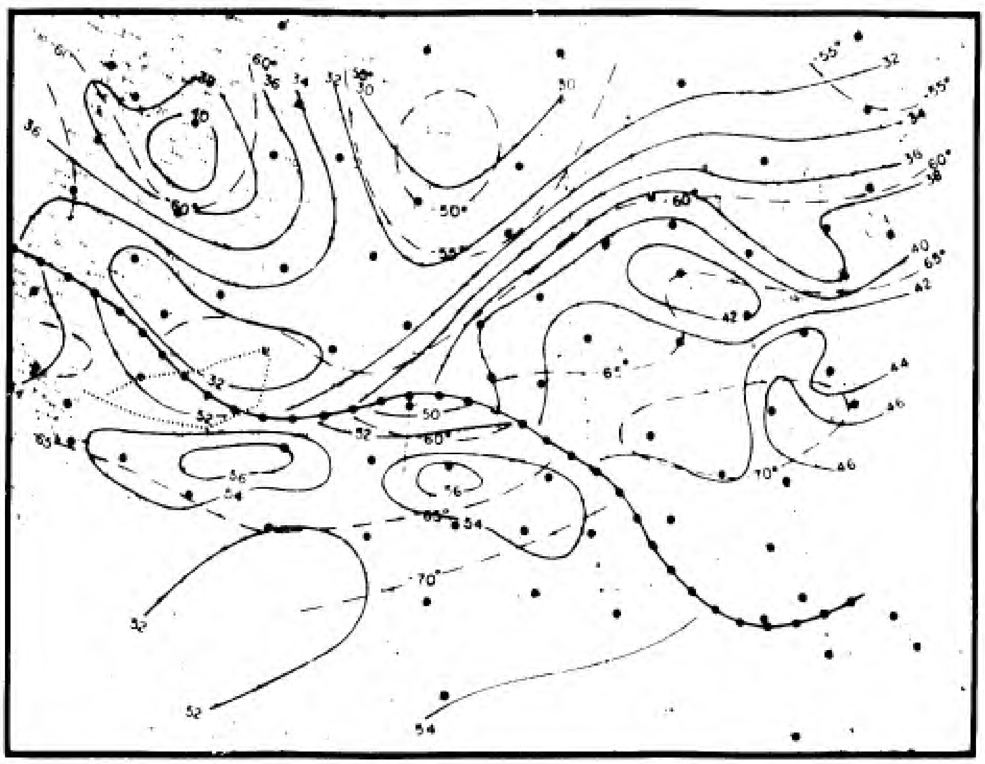

FIG. A-15 TROPOPAUSE CHART, 0000 GMT, 30 APRIL 1960

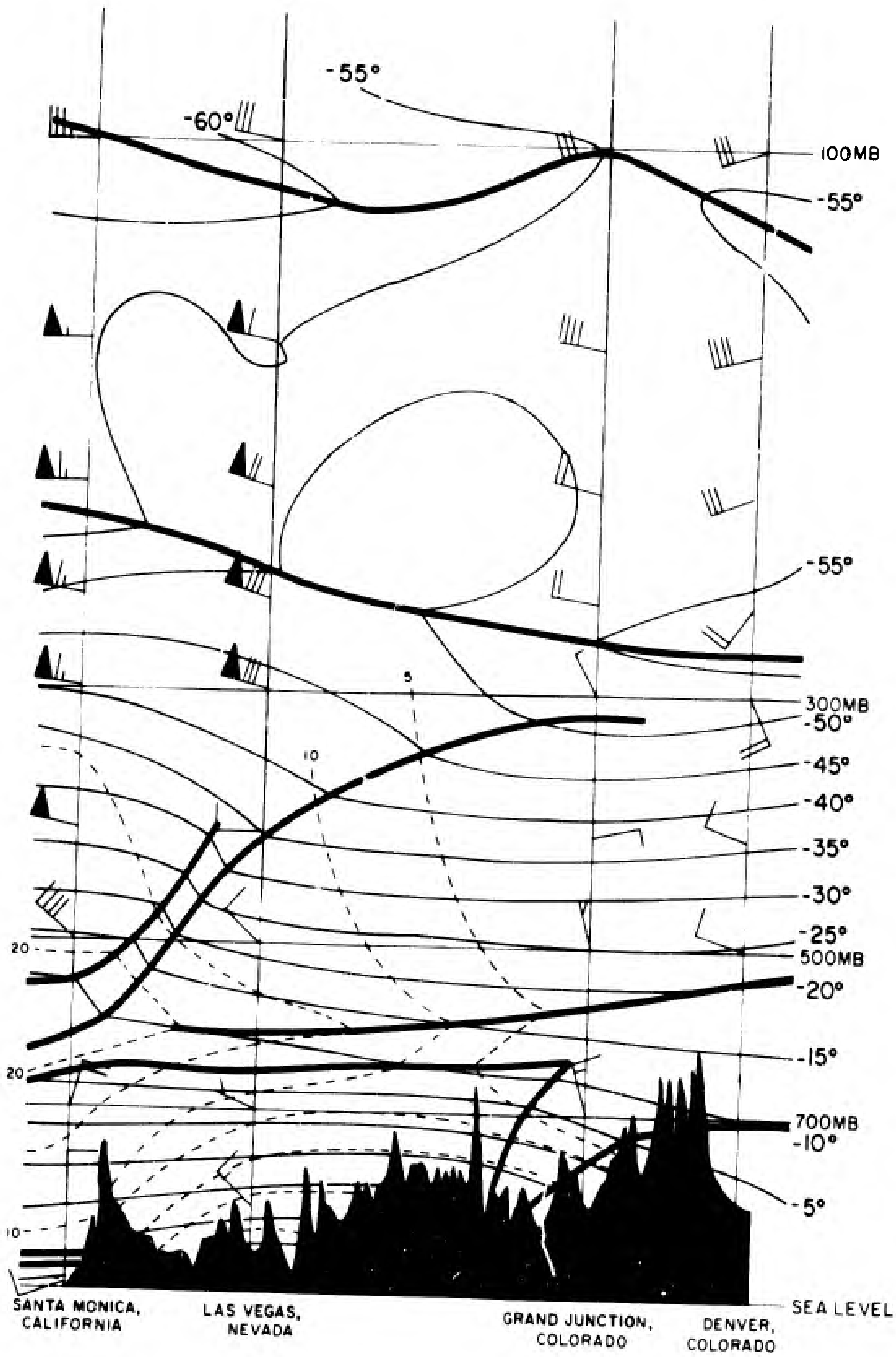

FIG. A-16 ATMOSPHERIC CROSS SECTION, 0000 GMT, 30 APRIL 1960

Fig. A-15. At Denver and Grand Junction, the two tropopauses have temperatures slightly colder than -55°C but the lower tropopause is colder than the upper. At Santa Monica and Las Vegas the upper tropopause is -60°C or colder, while the lower tropopause is 5 to 10°C warmer. Very little change in wind direction or speed takes place at the level of the lower tropopause at the latter two stations indicating, together with the temperature structure, that the upper tropopause is the major boundary between the troposphere and stratosphere.

A-2.3 Hourly Cloud and Weather Observations

Surface observations of cloud cover and thunderstorms were examined for the period 1800 to 2300 GMT. Analyses of these observations are shown in Fig. A-17. During the period several stations reported cumulonimbus and thunderstorms. Generally such observations were from widely separated stations and were not repeated during the following hour, indicating that the thunderstorms either moved out of view of the observer or dissipated. The most persistent area of thunderstorm was the one shown over southern Utah. Although the boundaries of this area showed considerable change in location during the early hours, a general area of thunderstorms gradually developed to cover much of southern Utah and northern Arizona. Much of the development in the area took place after the U-2 had flown over the area as indicated by the boundaries of the thunderstorm areas and the position of the U-2 at the time of the map.

The general pattern shown by the cirrus clouds during the period is a gradual expansion of the area over which such clouds were observed. This pattern is somewhat indefinite over some parts of the area, primarily northern Colorado, because of overcast skies below the cirrus level. Over the remainder of the area, however, observers were not restricted by low overcast.

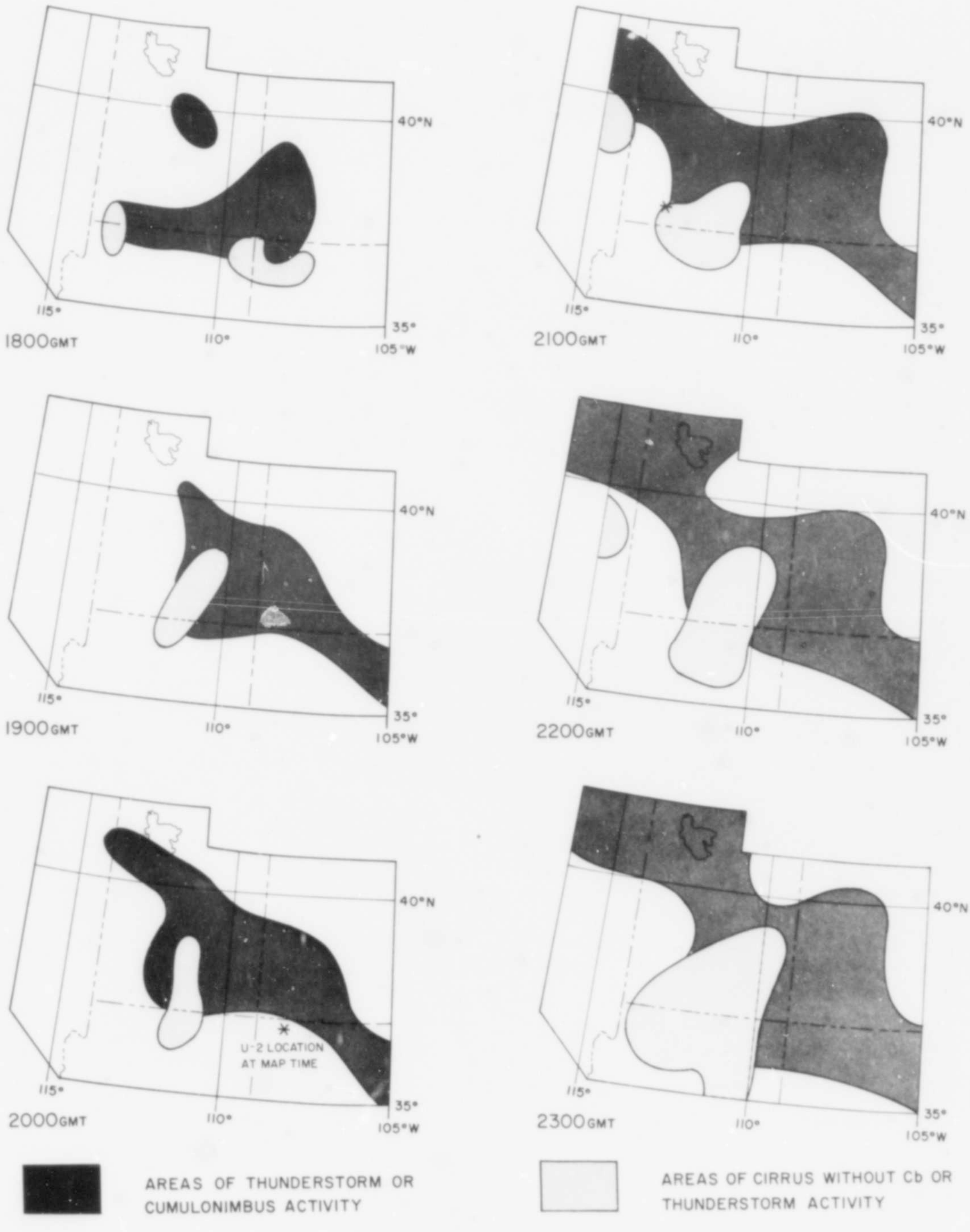

FIG. A-17 HOURLY NEPHANALYSES OF CLOUD COVER FOR 29 APRIL 1960 CASE STUDY

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