AFCRL-63-413

Scientific Report 1

A METEOROLOGICAL STUDY OF COLD CLOUDS AS RELATED TO SATELLITE INFRARED HORIZON SENSORS

Prepared for:

GEOPHYSICS RESEARCH DIRECTORATE
AIR FORCE CAMBRIDGE RESEARCH LABORATORIES
OFFICE OF AEROSPACE RESEARCH
UNITED STATES AIR FORCE
BEDFORD, MASSACHUSETTS

CONTRACT AF 19(628)-1681

By: *John E. Alder*

STANFORD RESEARCH INSTITUTE

MENLO PARK, CALIFORNIA

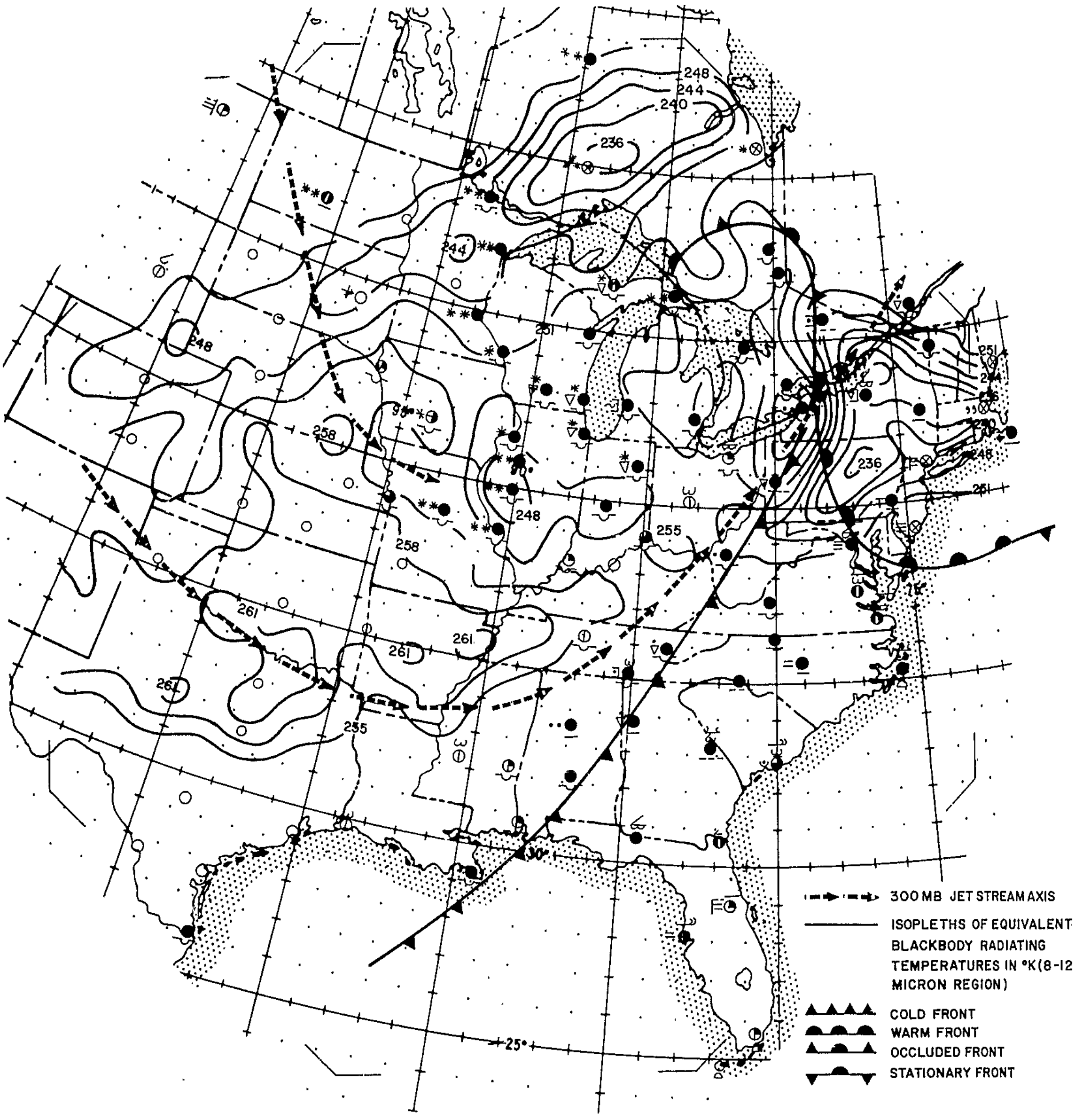


FIG. 34 OVERLAY OF SELECTED SURFACE, UPPER AIR AND INFRARED DATA FOR EXTRATROPICAL CYCLONE OVER GREAT LAKES (1100-1200 GMT, 29 November 1960)

ERRATUM

For the report, "A Meteorological Study of Cold Clouds as Related to Satellite Infrared Horizon Sensors," by John E. Alder; Scientific Report 1, Contract AF 19(628)-1681, AFCRL-63-143.

Figure 34, p. 42, was printed by error on standard report stock, rather than on vellum, and bound into the report. A vellum overlay of Fig. 34, to be used in conjunction with Fig. 35, is supplied herewith.

STANFORD RESEARCH INSTITUTE
MENLO PARK, CALIFORNIA
SRI

February 1963

AFCRL-63-413

Scientific Report 1

A METEOROLOGICAL STUDY OF COLD CLOUDS AS RELATED TO SATELLITE INFRARED HORIZON SENSORS

Prepared for:

GEOPHYSICS RESEARCH DIRECTORATE
AIR FORCE CAMBRIDGE RESEARCH LABORATORIES
OFFICE OF AEROSPACE RESEARCH
UNITED STATES AIR FORCE
BEDFORD, MASSACHUSETTS

CONTRACT AF 19(628)-1681

By: *John E. Alder*

SRI Project No. 4304

Approved:

MYRON G. H. LIGDA, MANAGER AEROPHYSICS LABORATORY

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

Copy No. 41

ABSTRACT

A cold cloud is defined as one that radiates infrared energy at a low temperature (about 200°K). The problems that present infrared horizon sensors on space vehicles are experiencing from cold clouds are discussed. Efforts to design new sensors to overcome these problems are also mentioned. Conditions favorable for cold clouds are described as the high, cold tropopause of a tropical air mass and a weather disturbance in this tropical air capable of generating dense cirriform clouds near the cold tropopause and associated lower opaque clouds to shut off radiation from lower levels. These weather disturbances may be in the form of an active Intertropical Convergence Zone, tropical cyclones, monsoons and extratropical cyclones. Distributions of these conditions favorable for cold clouds over the earth are discussed and illustrated with photographs. Particular emphasis is placed on the possibilities for cold clouds associated with an extratropical cyclone. Specific examples of this type of storm are studied, including one that was viewed by the infrared sensors of Tiros II. A model is formulated showing the location of an area favorable for cold clouds in an occluding extratropical cyclone. The association of a poleward-moving jet stream with a poleward-extending area favorable for cold clouds in an extratropical cyclone is noted. Therefore, a longitudinal frequency distribution of such areas is implied in a longitudinal frequency distribution of poleward-moving jet streams.

CONTENTS

ILLUSTRATIONS

ACKNOWLEDGMENTS

The author wishes to thank Messrs. Sidney M. Serebreny and Roy H. Blackmer, Jr. of the Aerophysics Laboratory of Stanford Research Institute for their supervision, guidance, and many helpful and valuable suggestions during the preparation of this study. He also wants to acknowledge the participation of Dr. Paul Davis, also of the Aerophysics Laboratory, for many helpful discussions during the course of the study. Thanks are also due Mrs. Arlyne Burris for her work in drafting the figures.

I INTRODUCTION

Several U.S. satellites and space vehicles--such as Mercury, Discoverer, and Nimbus--derive their attitude control from infrared sensors that detect the infrared radiation boundary between cold space and the relatively warm earth. Recently there has been much concern over the ability of these sensors to detect the earth-space boundary accurately. This concern has been mainly due to the inability of current infrared horizon sensor designs to distinguish clearly between a transition from warm earth to cold space and a transition from warm earth to a sheet of high cold clouds near the horizon. In other words, the sensors cannot reliably distinguish between the infrared radiation return from cold space and the infrared return from these high cold clouds. As a result, the sensors may erroneously interpret a cold cloud boundary that may occur near the horizon as the true earth-space interface. A cold cloud may be defined as one that radiates infrared energy at a low temperature (about $200^{o}K$). Its infrared radiation characteristics are quite similar to those of space.

Designers are attempting to solve the cold cloud problem by incorporating into their designs infrared sensors sensitive to radiation that is strongly absorbed by the atmosphere. The basis for this approach is that currently operational sensors are mainly sensitive to infrared radiation emitted by the earth in the 8-13 micron "window" region. (Infrared radiation in this bandwidth is transmitted with little absorption through the atmosphere.) As can be seen in Fig. 1, this type of sensor experiences a sharp drop in energy level when sighting on a cold cloud rather than the earth. The sensor interprets this drop in energy in the same way as passage across the space-earth interface and may temporarily adjust vehicle attitude as much as several degrees in error, depending on the extent of the cold clouds. Therefore, present recommendations for future horizon sensor designs indicate they should be sensitive to longer wavelengths, such as the 14-16 micron band (See Hanel, Bandeen and Conrath, 1962). In this band, atmospheric CO_2 strongly absorbs infrared radiation

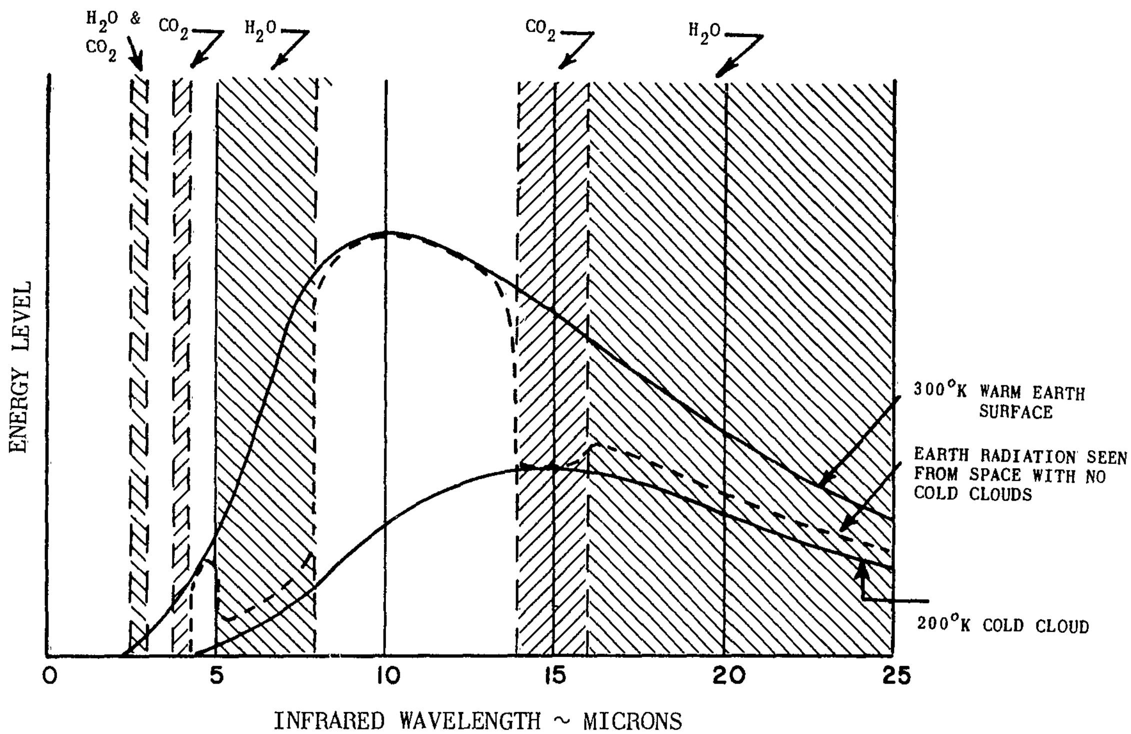


FIG. 1 INFRARED SPECTRUM DIAGRAM ILLUSTRATING COLD CLOUD PROBLEM
(From Aviation Week, 1 Oct. 1962)

emitted from the earth (See Fig. 1). Therefore, a sensor responsive to these wavelengths would detect relatively little difference in energy level between attenuated earth radiation and that of extremely cold, high-altitude clouds, and probably would be less likely fooled by these clouds as are earlier sensor designs.

These advanced sensors may solve the cold cloud problem, but at this point, there are still some uncertainties in their design and development. If these new sensors are not completely successful, a study such as this of the nature of cold clouds and their distributions over the earth could prove useful in operational programming of satellites to attempt to cope with this adverse effect.

In this study, the nature of cold clouds is discussed first; geometrical considerations pertinent to viewing these clouds near the horizon from a satellite are then presented; and finally, the distribution of these clouds over the earth is discussed.

II THE NATURE OF COLD CLOUDS

A cold cloud is generally defined as a cloud surface that acts as a low-energy infrared radiator at a temperature of about 200°K. As one might suspect, in order for a cloud to have a temperature as low as 200°K, it must be located at considerable altitude. In looking at representative temperature soundings for various types of air masses (Fig. 2), it is seen that the coldest temperature in each air mass type is generally found at the tropopause and that, significantly, the coldest tropopause temperature of all air mass types is in a tropical air mass. Temperatures on the order of 200°K or less are indicated near the tropical tropopause, so it is apparent that any clouds located in this region meet the temperature criteria of cold clouds. Clouds of the cirriform type do occur near the tropical tropopause and are generally associated with weather disturbances such as an active Intertropical Convergence Zone, monsoons, tropical storms, and extratropical cyclones in the middle latitudes.

In order for cirriform clouds to present extremely cold infrared temperatures to a satellite, little or no infrared radiation must filter through from the ground. Dense cirriform clouds near the cold tropical tropopause, associated with lower opaque clouds that effectively shut off radiation from low levels, should thus appear really cold to a satellite infrared sensor. Although cirriform clouds may occasionally be found in arctic and polar air, or in tropical air not associated with lower opaque clouds, it is not believed that the radiation returns of these cirriform clouds would really classify them as cold clouds. This is because the tropopauses of polar or arctic air are relatively warm (See Fig. 2) and because cirriform clouds by themselves are somewhat transparent to warmer radiation from below. Therefore, it has been assumed in this study that cold clouds are synonymous with dense cirriform clouds in tropical air that are associated with lower opaque clouds and are produced by weather disturbances.

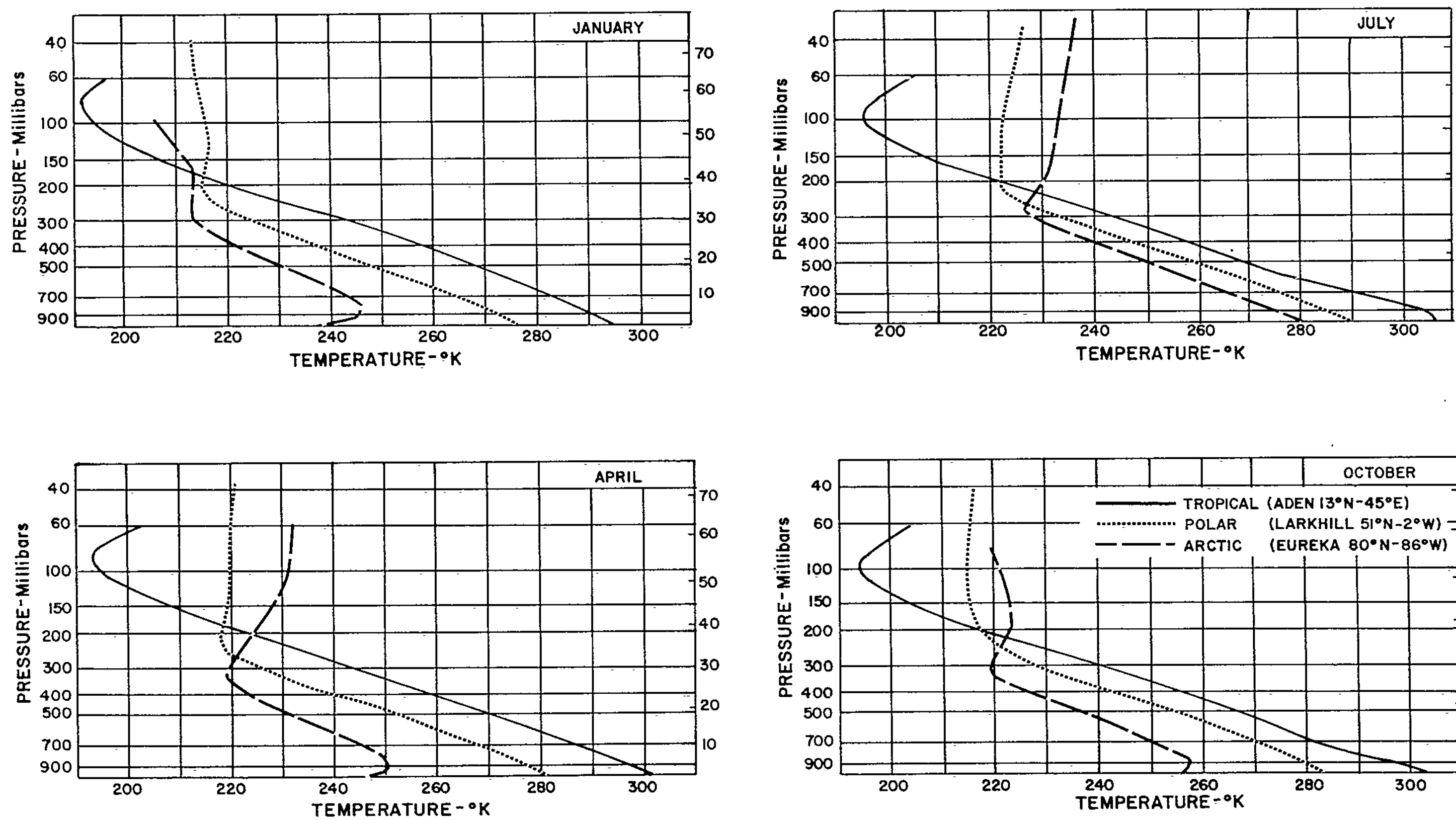


FIG. 2 AVERAGE TEMPERATURE SOUNDINGS OF VARIOUS AIR-MASS TYPES DURING THE MID-SEASON MONTHS
(From Goldie, Moore and Austin, 1958)

III GEOMETRICAL CONSIDERATIONS

The geometry of a satellite horizon sensor viewing toward the horizon is important in any consideration of cold clouds. Figure 3 illustrates this geometry. As can be seen, a cloud area existing directly above the horizon point does not obstruct the sensor line-of-sight to the horizon, but must be somewhat closer to the satellite along the line-of-sight. An effect apparent in the geometry is that the first degree or two below the horizon, as observed from a satellite, encompasses a considerably wider area on the earth than the same angular increment several degrees below the horizon. The magnitudes of these areas viewed over long distances by a satellite indicate that extended cloud systems associated with meso- or synoptic-scale weather disturbances, rather than individual cloud elements, are most likely to affect the horizon sensors significantly. Also, the minimum width of a band of cold clouds corresponding to a particular angular error in horizon location increases as the orbital altitude of the satellite increases. These effects are indicated in Fig. 4 by curves based on the following assumptions:

(1) Cold clouds at an altitude of 10 nautical miles (approx. 60,000 feet),

(2) A perfectly spherical earth,

(3) No atmospheric refraction, and

(4) An effective infrared earth-space interface at about 20,000 feet altitude.

The last assumption takes into account infrared radiation from the atmosphere itself and is an estimate based on curves presented by Hanel, Bandeen and Conrath (1962) for the 8-12 micron atmospheric window region. As far as the other assumptions are concerned, cold clouds may occur a few thousand feet below an altitude of 10 nautical miles (See Fig. 2), but it is believed that this variation plus those due to a non-spherical earth and atmospheric refraction, would produce only minor changes in the results shown. As an example of the relationships indicated in

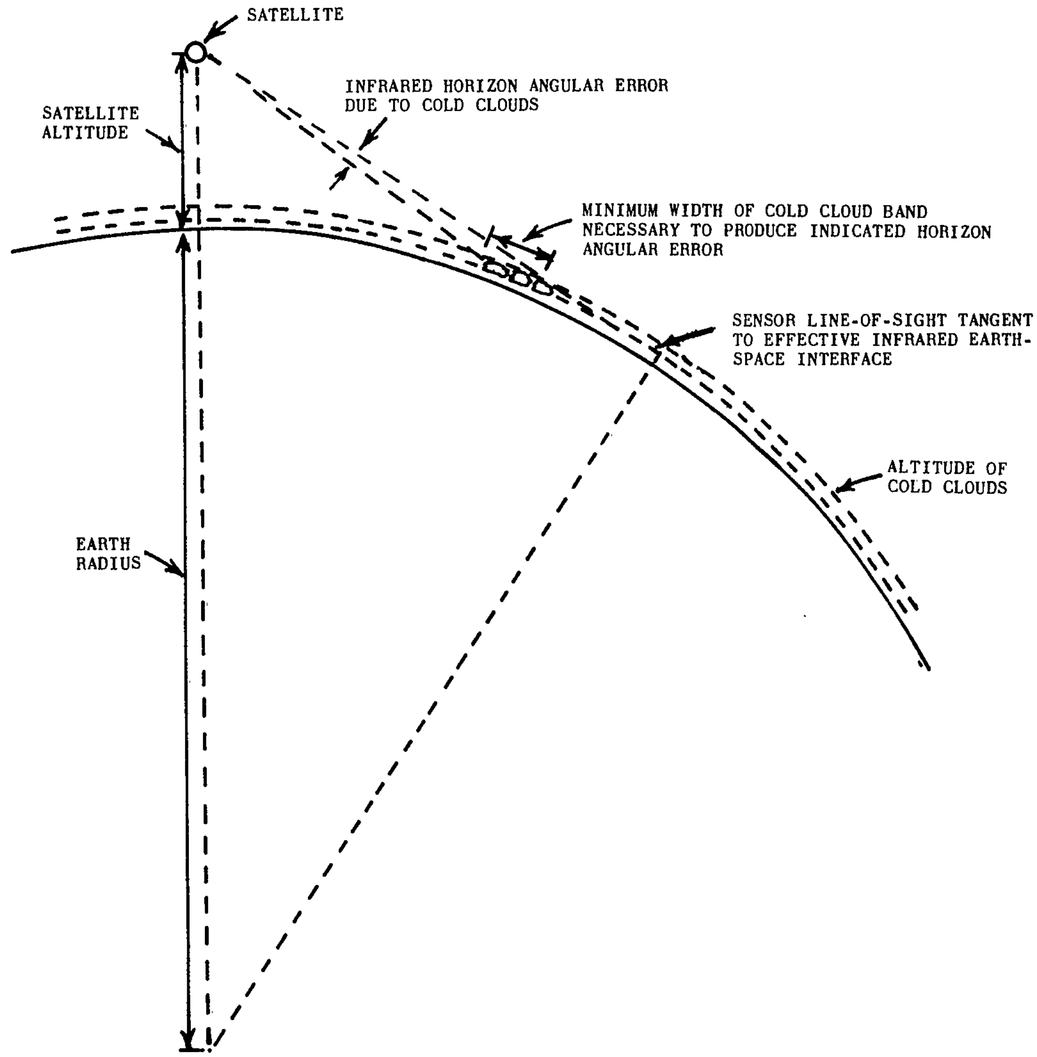


FIG. 3 GEOMETRY OF SATELLITE HORIZON SENSOR VIEWING COLD CLOUDS TOWARD HORIZON

Fig. 4, a band of cold clouds about 200 nautical miles wide could cause an angular error in horizon location of about 2^{0} in a satellite orbiting at an altitude of 100 nautical miles; whereas it would require a band of cold coulds about twice as wide to cause a similar angular error in a satellite orbiting at 500 nautical miles altitude.

Another important geometrical aspect of the cold cloud problem is the variation of that portion of earth visible from a satellite. Figure 5 indicates the portion of the earth visible from a satellite at various orbital altitudes. The visible portion is represented by the distance from the sub-point (point directly below satellite) to the horizon, measured both linearly and angularly. An increase in visible portion is noted as orbital altitude of the satellite increases. For example, a satellite orbiting at 100 nautical miles altitude can view almost 15^{0} of earth surface in any direction; while a satellite orbiting at 500 nautical miles altitude can view almost 30^{0} of earth surface in any direction. The significance of these data is that not only may a satellite orbiting at 100 nautical miles altitude observe, at one instant, cold clouds near the horizon that are related to systems in the middle latitudes and tropics of one hemisphere, but also the higher orbiting satellites may, at one instant, observe cold clouds near the horizon associated with systems in the middle latitudes of the northern hemisphere as well as cold clouds associated with systems in the middle latitudes of the southern hemisphere.

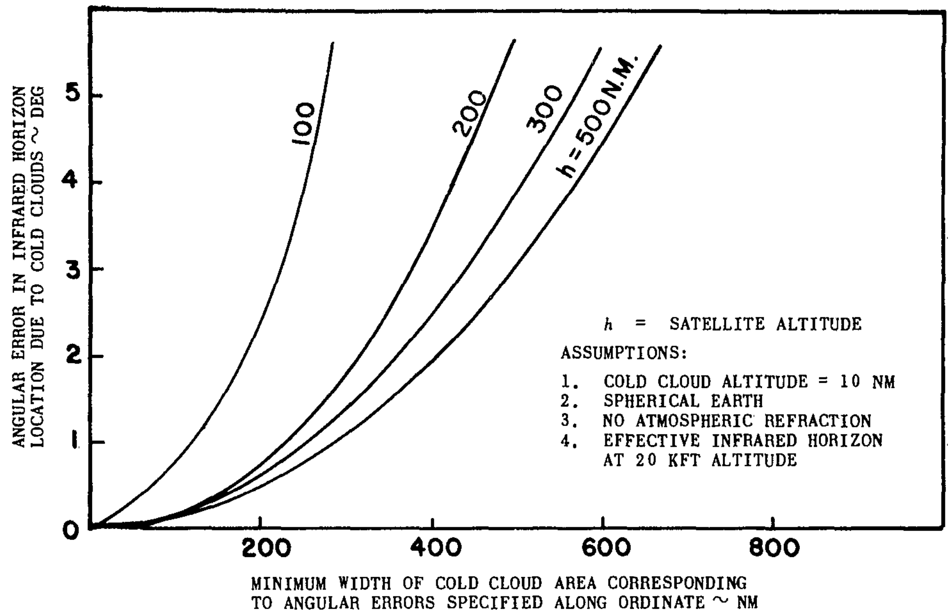


FIG. 4 RELATIONSHIP BETWEEN SATELLITE INFRARED HORIZON ANGULAR ERROR AND COLD CLOUD EXTENT NEAR HORIZON

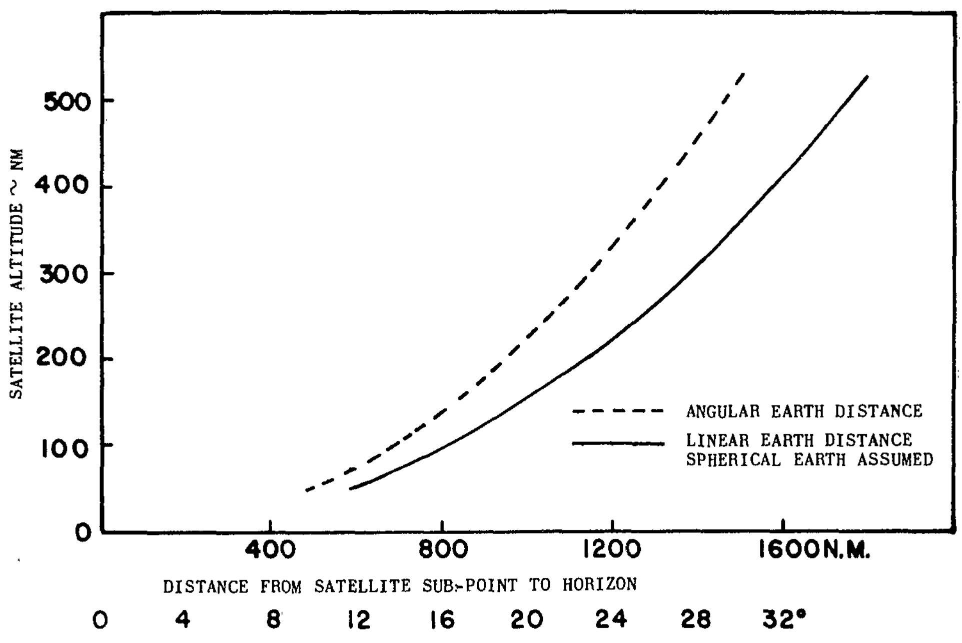


FIG. 5 PORTION OF EARTH VISIBLE FROM A SATELLITE AT VARIOUS ORBITAL ALTITUDES

IV DISTRIBUTION OF CONDITIONS FAVORABLE FOR COLD CLOUDS

A. GENERAL

Cold clouds are found near the cold tropopause of tropical air masses and are associated with other opaque clouds and weather disturbances. Therefore, a distribution of clouds of this type over the earth must be related to the horizontal distribution of tropical air over the world as well as weather disturbances associated with this tropical air. Accordingly, the distribution of such meteorological features has been investigated. In the following discussion of these features, examples of observed cloud distributions are shown, when appropriate, and areas delineated where conditions are favorable for cold clouds.

B. COLD TROPOPAUSE DISTRIBUTION

Figure 6 shows the average distribution of temperatures at the tropopause over most of the world for the four mid-months of each season (Goldie, Moore and Austin, 1958). The tropical tropopause is shown overlapping the polar tropopause in that region where the frequency of occurrence of both is greater than 10%. The overlapping regions are in those latitude belts where frequent extratropical cyclones traverse. Quite often, tropical air advection (i.e., transport) occurs considerably farther poleward than indicated in these average distributions. Such advection is usually concomitant with development of a blocking anticyclone into high latitudes. As an illustration of this situation from the reference cited, Fig. 7 is a sounding made at Cold Bay, Alaska (55°N, 163°W), at 0000 GMT, 21 May 1960 (Serebreny, Wiegman and Hadfield, 1962). Note the cold tropopause of this sounding similar to that typifying a tropical air mass in Fig. 2.

Returning to the maps of average distribution of tropopause temperatures (Fig. 6), one can see that temperatures of 200°K or less occur continuously over the region 20°S-20°N latitude, with some poleward drift during the summer season. On the average, tropopause temperatures

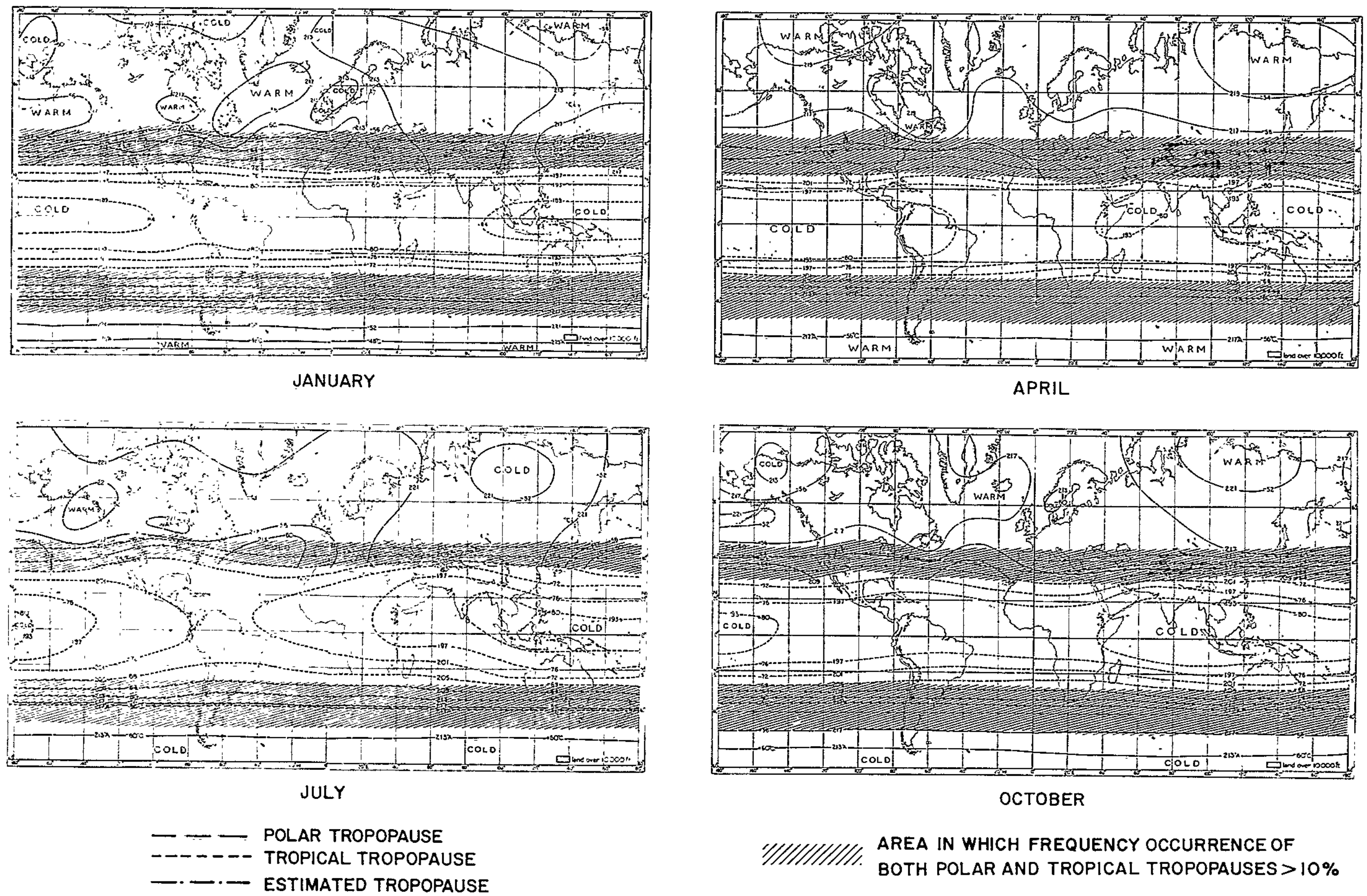


FIG. 6 AVERAGE TEMPERATURES AT THE TROPOPAUSE DURING THE MID-SEASON MONTHS
(From Goldie, Moore and Austin, 1958)

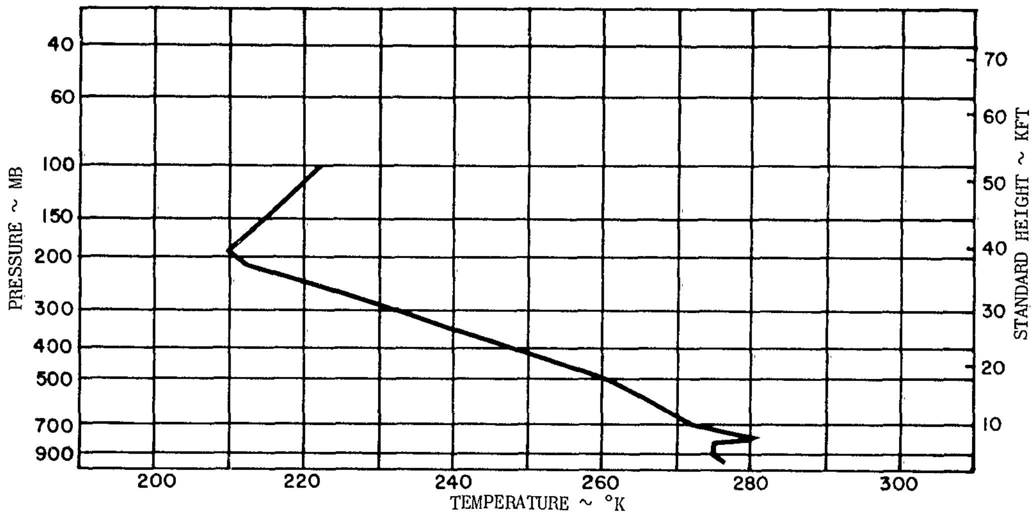


FIG. 7 TEMPERATURE SOUNDING – COLD BAY, ALASKA (55°N, 163°W)
(0000 GMT, 21 MAY 1960)

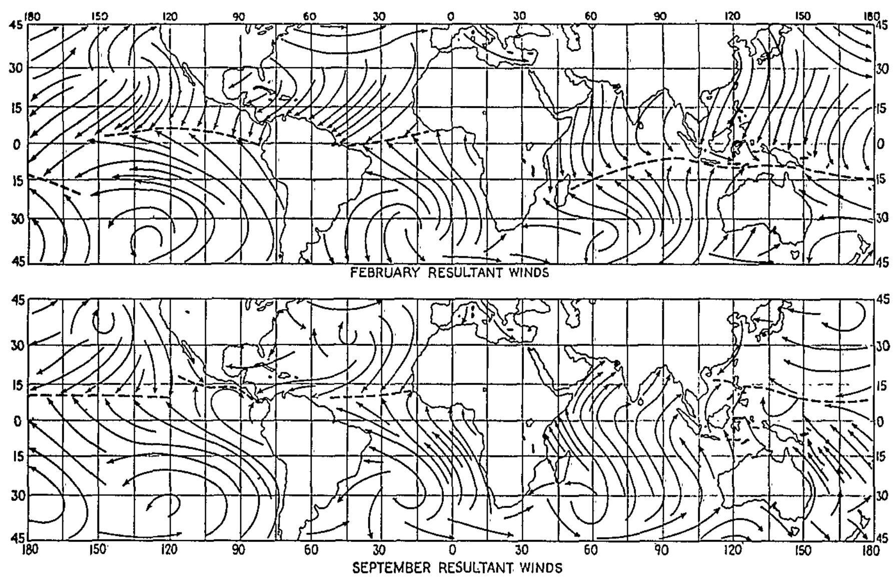


FIG. 8 SEPTEMBER AND FEBRUARY MEAN POSITIONS OF ITCZ AND DISTRIBUTION OF RESULTANT SURFACE WINDS OVER THE OCEANS
(From Byers, 1959)

increase slowly poleward but can still be as low as 210°K as far north and south as 40° latitude. The upper limit of cold cloud temperatures that can still cause trouble with satellite infrared horizon sensors has not been established, but is assumed to be somewhere near 210-215°K in this study.

C. INTERTROPICAL CONVERGENCE ZONE

In addition to a favorable temperature structure, cold cloud formation also requires the presence of a weather disturbance of some kind in the tropical air mass. As mentioned earlier, this disturbance may be in the form of an active Intertropical Convergence Zone (ITCZ). The ITCZ is that region in the tropics where the trade winds from the northern and southern hemispheres meet. This boundary migrates seasonally, on the average, about 15° north and south of the equator in some places, reaching its northernmost point in September and southernmost in March, corresponding to the seasons of highest temperatures in the oceans (See Fig. 8). Migration of the zone is in the form of a progression of surges and hesitations dependent on the relative strengths of the opposing trades. During these surges, the juxtaposition of relatively cooler and warmer air produces frontal activity with associated weather, thunderstorms, and multiple cloud layers, including cirriform clouds reaching the vicinity of the tropical tropopause. This band of weather activity may extend up to several hundred nautical miles in width, as indicated by the extensive bright cloud areas in a sequence of TIROS III satellite photographs (Fig. 9), so generously provided by Col. James C. Sadler of the International Indian Ocean Expedition. However, at times between surges, the zone becomes so weak that it can hardly be located and little or no weather or cloudiness can be found along it. Figure 10 shows a sequence of TIROS I satellite photos taken on 12 April 1960 as the satellite was passing southeasterly across the ITCZ just off the north-east coast of South America. The ITCZ is represented by the bright band stretching from left to right in the photos. The bright patches indicate heavy clouds and precipitation which are believed associated with dense cirriform clouds near the tropical tropopause. Figure 11 shows a map of the area photographed in Fig. 10, with closest available surface

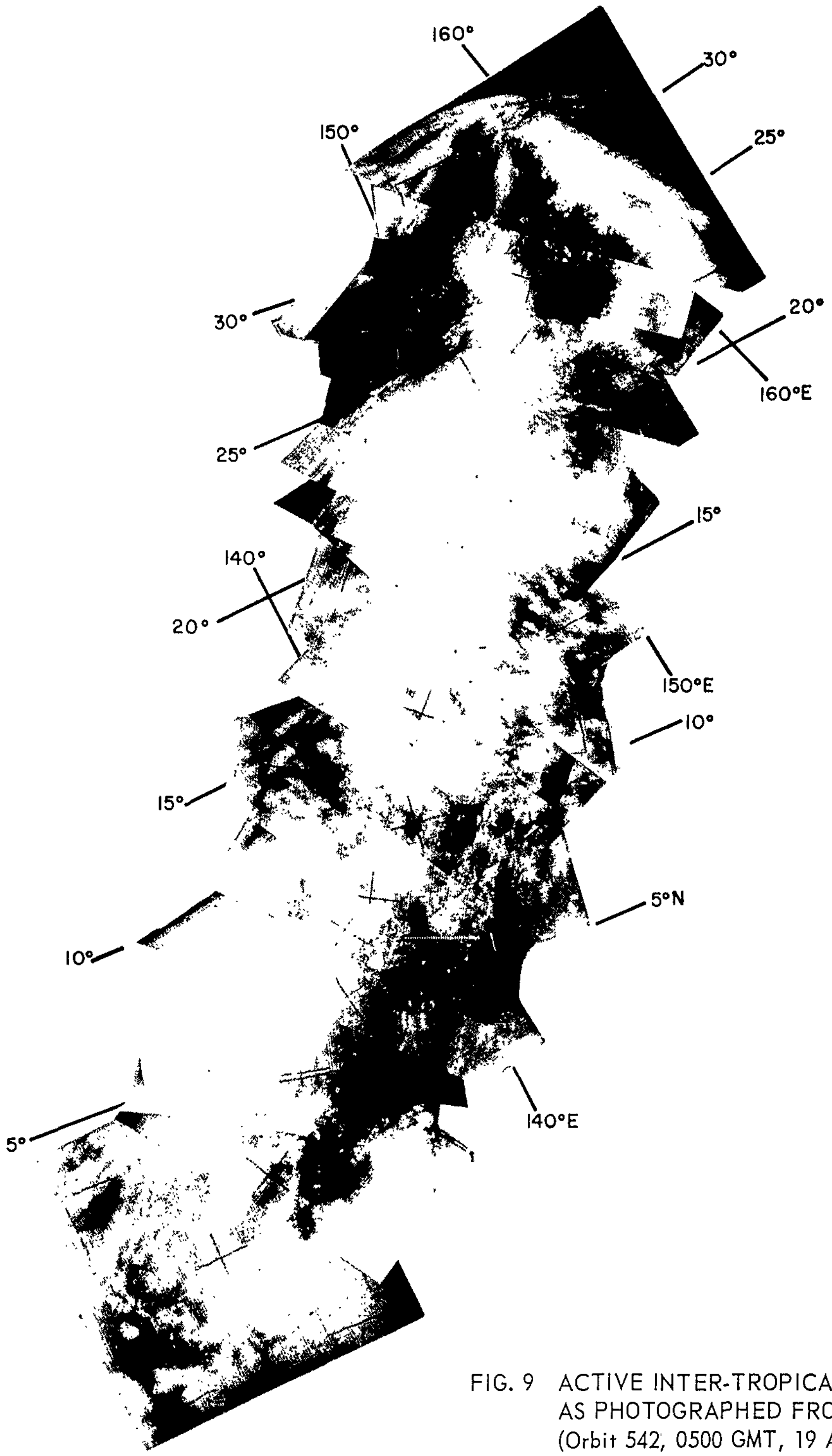


FIG. 9 ACTIVE INTER-TROPICAL CONVERGENCE ZONE
AS PHOTOGRAPHED FROM TIROS III
(Orbit 542, 0500 GMT, 19 Aug. 1961) (After Sadler)

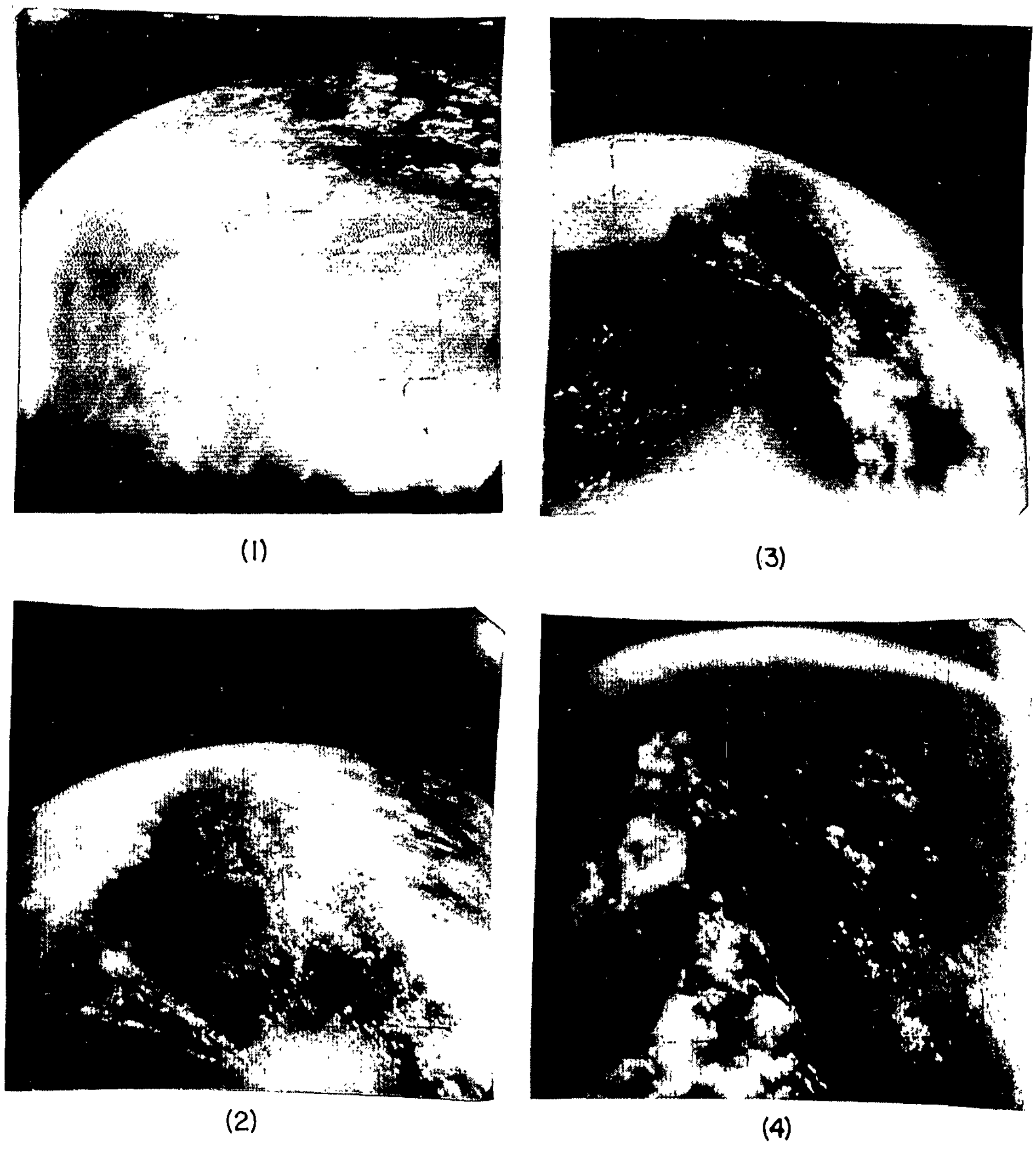


FIG. 10 TIROS 1 PHOTOGRAPHIC SEQUENCE ACROSS ITCZ ENTERING NORTHEASTERN SOUTH AMERICA (Orbit 162, 1400 GMT, 12 April 60)

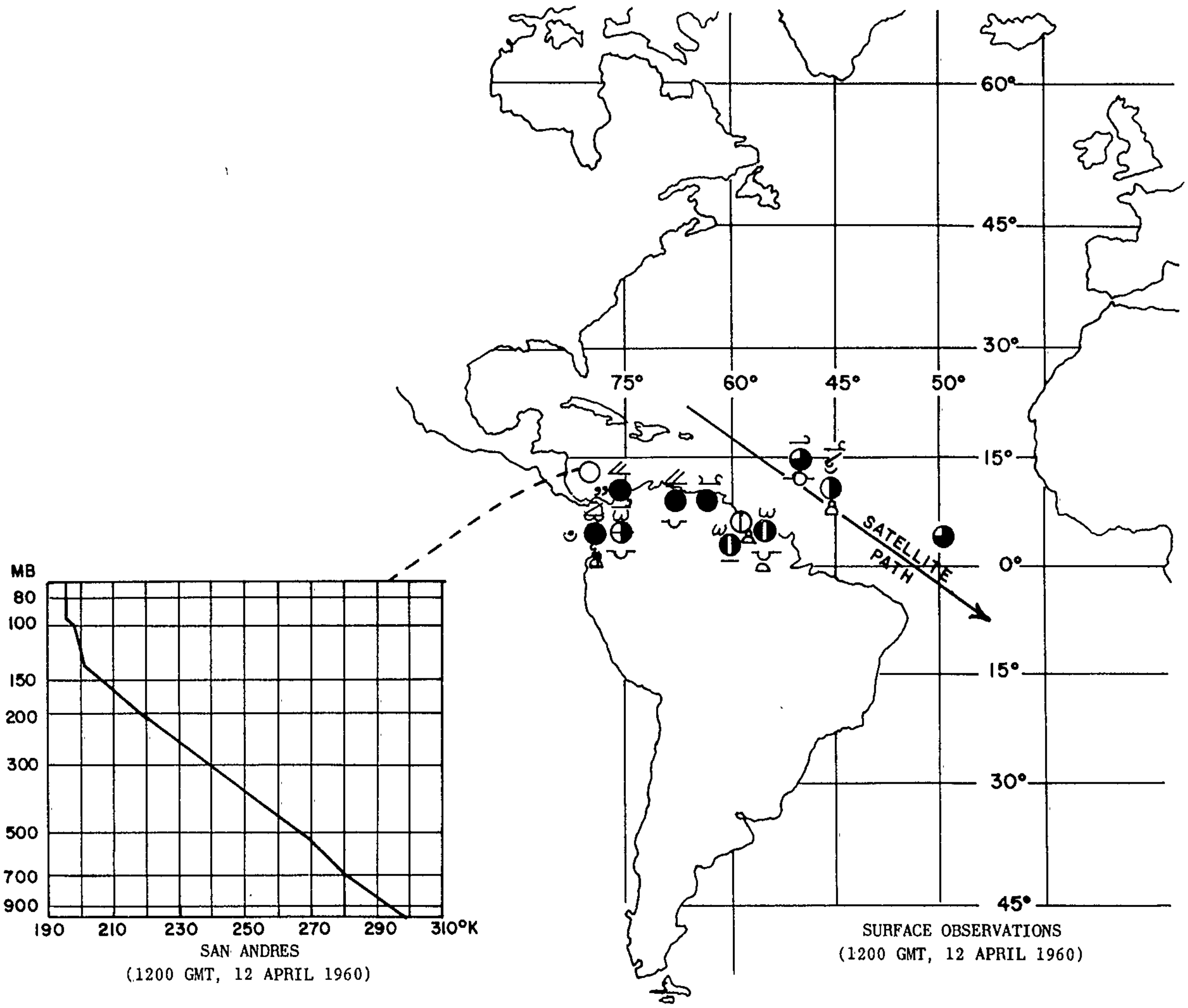


FIG. 11 CLOUD OBSERVATIONS AND TEMPERATURE SOUNDING IN VICINITY ABOUT PHOTOGRAPHIC TIME OF FIG. 10

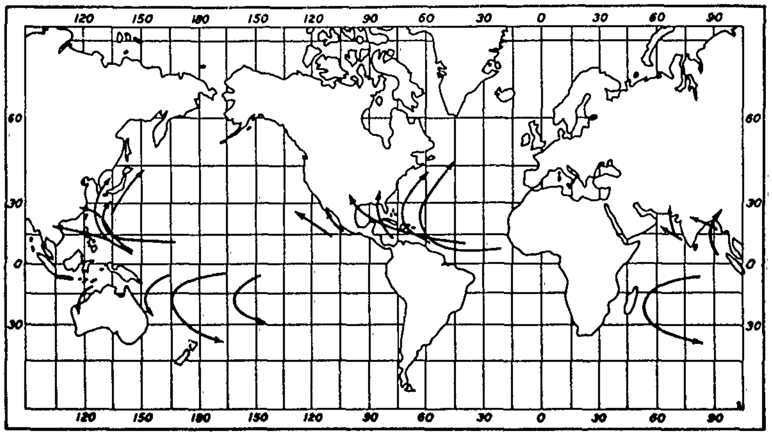
observations and radiosonde information plotted. Note the tropical nature of the sounding and surface reports of cirriform clouds associated with other opaque clouds such as towering cumulus, cumulonimbus, altostratus and altocumulus. (Explanations of cloud and weather codes appear in Appendix A.)

D. MONSOONS

Monsoon winds also produce significant areas of dense cirriform clouds associated with lower opaque clouds in tropical air. These winds result from oceanic air flowing into a weak low-pressure area developed over a land mass during the hot summer months. The moist air warms and rises over the land mass and generates heavy rains, thunderstorms and multilayer clouds building up to the vicinity of the tropopause. Figure 8 indicates that major monsoon regions are located in Central Africa, India, Southeast Asia, Australia and Northeast South America and are related to the seasons and migration of the Intertropical Convergence Zone.

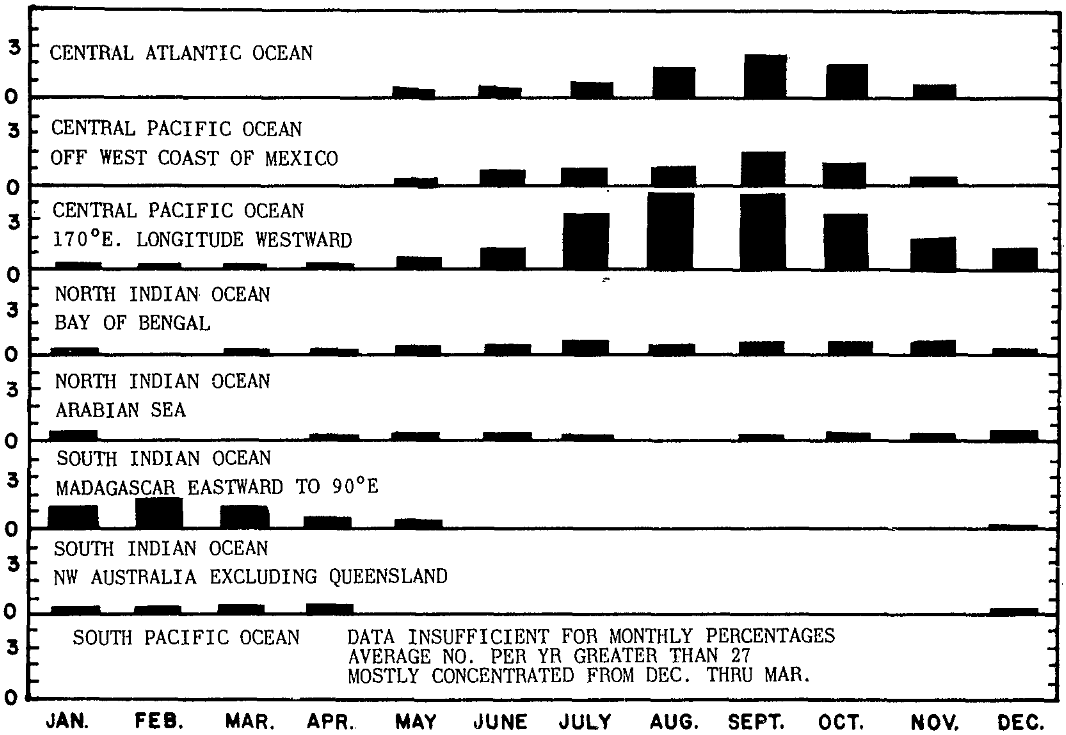
E. TROPICAL CYCLONES

Tropical cyclones are another important source of areas of dense cirriform and associated lower opaque clouds in tropical air. These storms originate in the tropics, but their life cycles and tracks may take them eventually into higher latitudes. They may vary in intensity from weak low-pressure areas of discontinuously squally weather with winds of 20 to 30 mph up to well-developed systems of heavy clouds and torrential rain with surface winds of 100 mph or more, better known as hurricanes or typhoons. The size of these storms can also vary from about 100 miles to about 1000 miles in diameter. The principal areas of formation and paths of tropical cyclones (Dunn and Miller, 1960) are indicated in Fig. 12. Conspicuously absent are tropical cyclones in the South Atlantic Ocean and Eastern South Pacific. This appears to be due to low ocean-surface temperatures and the negligible migration of the ITCZ south of the equator in those regions. Both high ocean-surface temperatures and appreciable migration of the ITCZ from the equator toward the source region seem to be prerequisites of tropical



(FROM DUNN AND MILLER, 1960)

FIG. 12 PRINCIPAL AREAS OF FORMATION AND PATHS OF TROPICAL CYCLONES



(FROM DUNN AND MILLER, 1960)

FIG. 13 AVERAGE MONTHLY FREQUENCIES OF TROPICAL CYCLONES BY SOURCE REGIONS cyclone formation. Figure 13 shows average monthly frequencies of tropical cyclones (Dunn and Miller, 1960) forming in the source regions indicated in Fig. 12. Note that far more tropical cyclones form in the West Central Pacific Ocean off the coast of Southeast Asia than in the other source regions. Not only are there more there, but they are quite often larger in size and more violent than elsewhere.

Figure 14 is a mosaic of photographs taken at 1815 GMT on 5 October 1954 from a rocket 100 miles above White Sands, New Mexico, and looking southeast toward a tropical storm (spiral cloud pattern in photograph) located near Del Rio, Texas (Hubert and Berg, 1955). The storm had moved westward from western Cuba on 2 October with surface winds up to 30 knots, then had continued across the Gulf of Mexico with little change, never developing into a hurricane. On 4 October, the center of the storm crossed the Texas coast about 40 miles north of Brownsville. During passage of this system, Brownsville recorded 3.09 inches of rain in 45 minutes and over 6 inches in 3 hours. During the day the photographs were made, the rainfall pattern associated with the storm decreased in intensity, then increased again when the storm moved over the Big Bend region of Texas and the southwestern corner of New Mexico, causing floods in the area of Roswell, New Mexico. The upper air sounding taken at 1545 GMT, 5 October 1954, at Del Rio, Texas, and surface observations taken in the vicinity about the time of the rocket photographs are indicated in Fig. 15. Once again, observe the high cold tropopause of tropical air in the sounding and several surface observations of cirriform clouds accompanied by other lower opaque types.

F. EXTRATROPICAL CYCLONES

1. General

The boundary zone between cold air from the polar regions and tropical air equatorward is also an important source of cold clouds in the middle latitudes. Extratropical cyclones, which are wave disturbances on this boundary or polar front, result in frequent poleward invasions

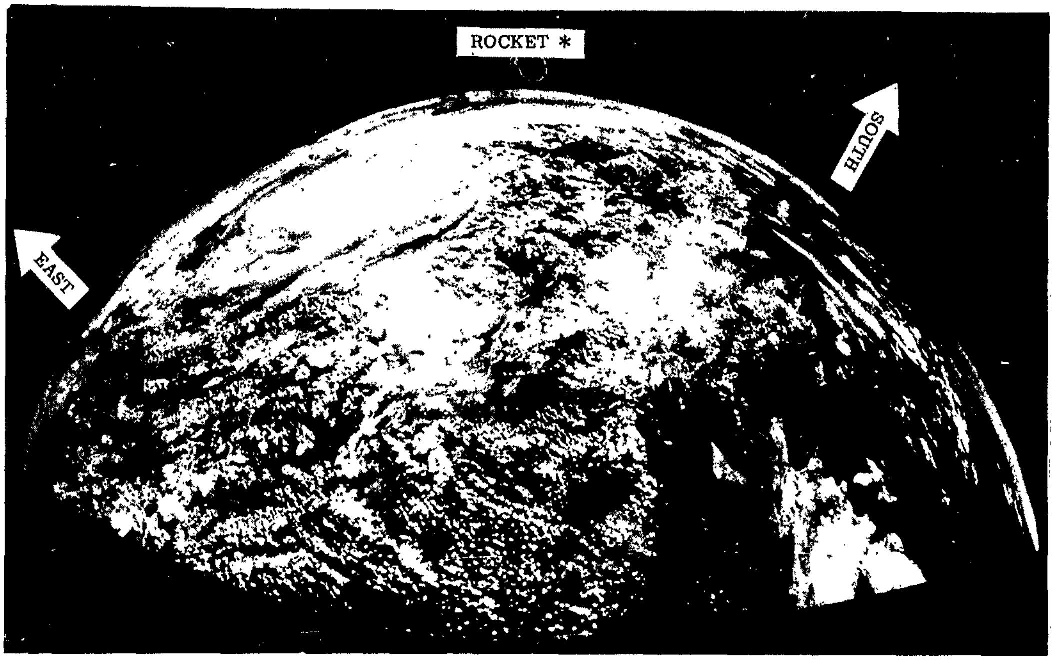
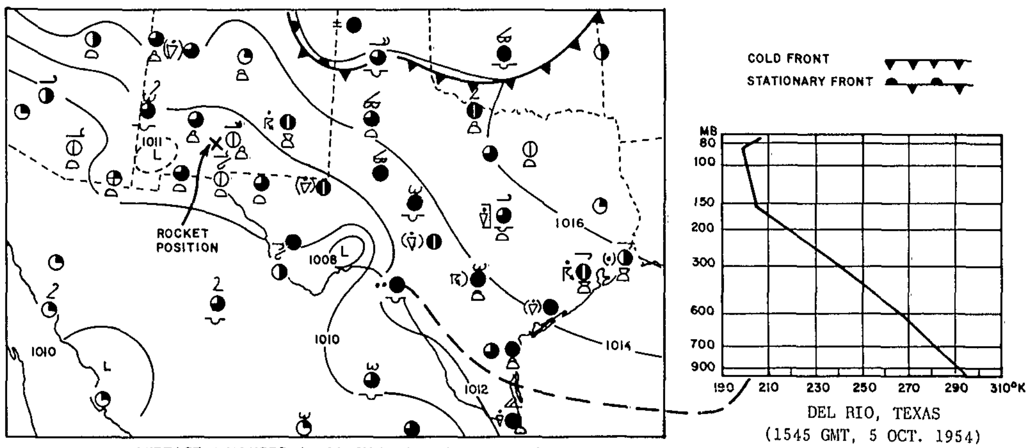


FIG. 14 MOSAIC OF ROCKET PHOTOGRAPHS OF TROPICAL STORM LOCATED NEAR DEL RIO, TEXAS (1815 GMT, 5 October 1954) (From Hubert and Berg, 1955)



SURFACE ANALYSIS (1830 GMT, 5 OCTOBER 1954)

FIG. 15 CLOUD OBSERVATIONS AND TEMPERATURE SOUNDING IN VICINITY ABOUT TIME OF PHOTOGRAPHIC MOSAIC IN FIG. 14

of tropical air to high latitudes. As noted in Fig. 6, a tropical tropopause may, on the average, extend as far north and south as 40-45° latitude over 10% of the time. This is primarily due to the periodic passage of extratropical cyclones through the middle latitude belts. Frequently, tropical air advection occurs to even higher latitudes in well-developed extratropical cyclones. Figure 16 shows where tropical air is transported poleward with respect to extratropical cyclones. The figure is based on a three-dimensional model (Bergeron, 1951) of successive extratropical cyclones moving eastward in the North Atlantic. Poleward advection of tropical air is indicated in the form of a tongue that rides up over the wave on the polar front associated with the cyclone. In the case of a young cyclone, i.e., before and during early occlusion, note that the tongue extends poleward mainly over the warm front portion. However, as the cyclone matures and becomes more occluded, the tongue not only extends poleward over the warm front but also circles cyclonicly back over the occluded portion. Note also that the jet stream is along the boundary between the tropical and polar air near the tropopause and that a poleward-moving jet stream is along the left boundary of the poleward-extending tongue of tropical air with its cold tropopause. Cloudiness is usually found in this tongue of tropical air, due to either ascent over the lower polar air or ascent caused by instability and low-level convergence before frontal upgliding. Near the cold tropopause, this cloudiness is generally of the dense cirriform type.

2. <u>Extratropical Cyclone Photographed by TIROS I over North Pacific</u>

To illustrate these characteristics, four examples of extratropical cyclones were studied. The first was centered at 48°N, 175°W in the North Pacific at the time the TIROS I satellite photographed it during Orbit 720 on 21 May 1960. This storm has been studied in detail elsewhere (Serebreny, Wiegman and Hadfield, 1962). Figure 17 shows the satellite photographs of the storm during Orbit 720. The 300-mb jet stream axis is superimposed on the satellite photographs and is further defined on the accompanying 300-mb map (Fig. 18). Figures 19 and 21 are the surface and tropopause temperature maps of the area, respectively. Figure 20 is an

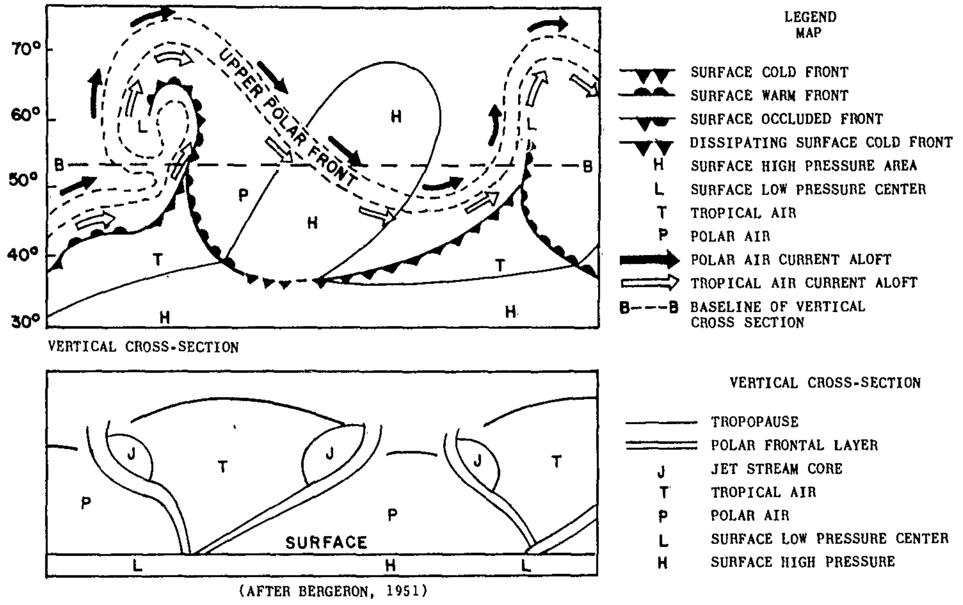


FIG. 16 THREE-DIMENSIONAL MODEL OF SUCCESSIVE EXTRATROPICAL CYCLONES IN THE MIDDLE LATITUDES OF THE NORTHERN HEMISPHERE (Typical Fall Conditions)

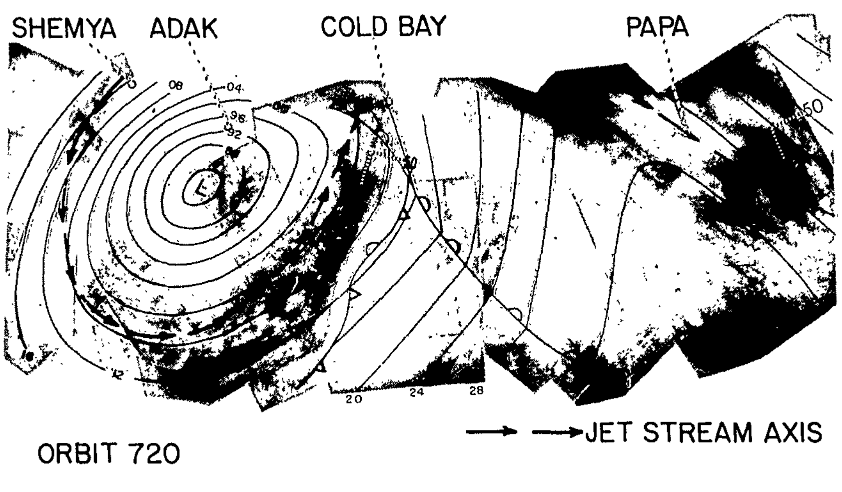


FIG. 17 TIROS I PICTURES OF EXTRATROPICAL CYCLONE IN NORTH PACIFIC WITH SUPERIMPOSED SURFACE AND UPPER AIR ANALYSES (0000 GMT, 21 May 1960) (From Serebreny, Wiegman and Hadfield, 1962)

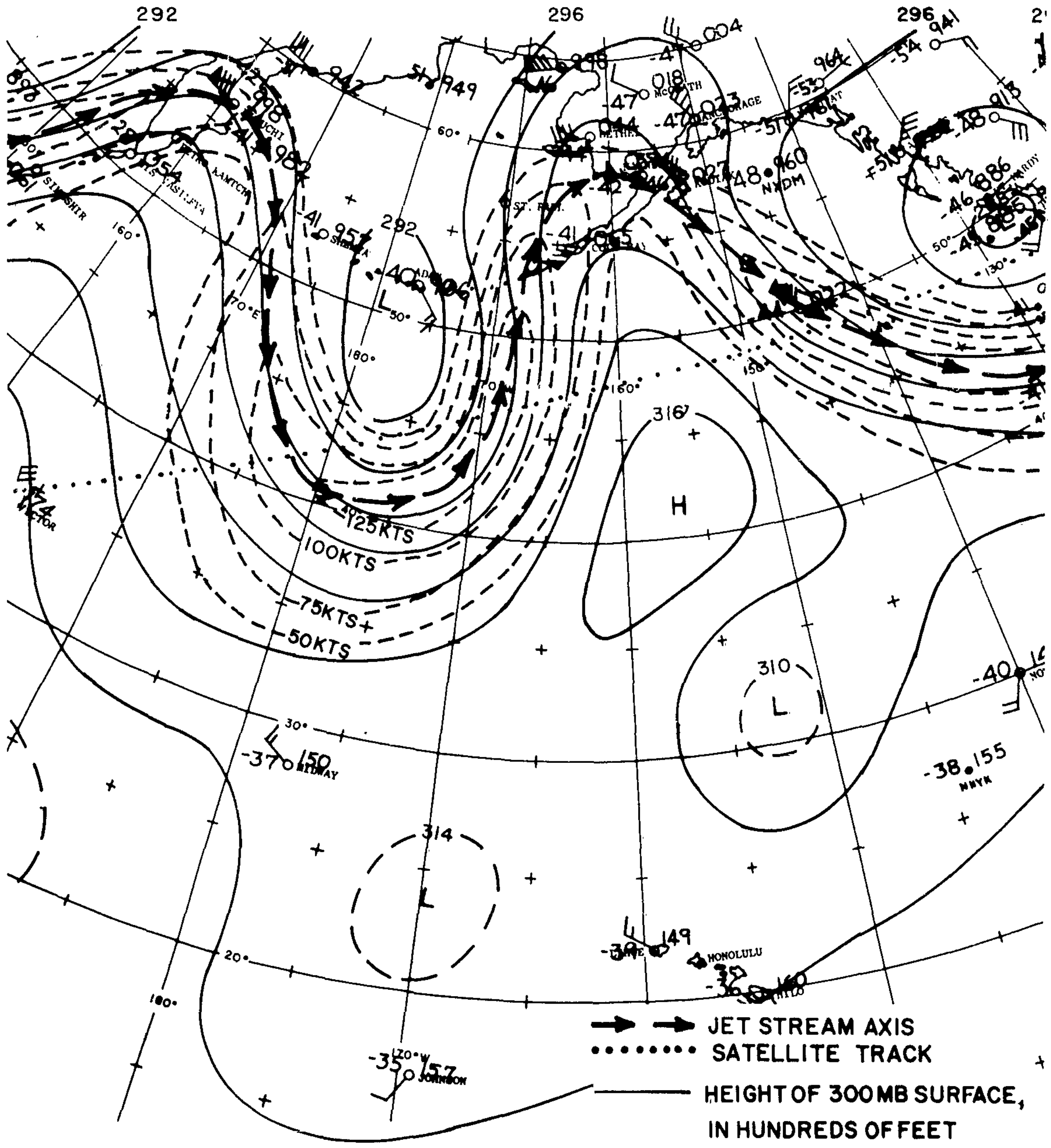


FIG. 18 300 mb MAP (0000 GMT, 21 May 1960) (From Serebreny, Wiegman and Hadfield, 1962)

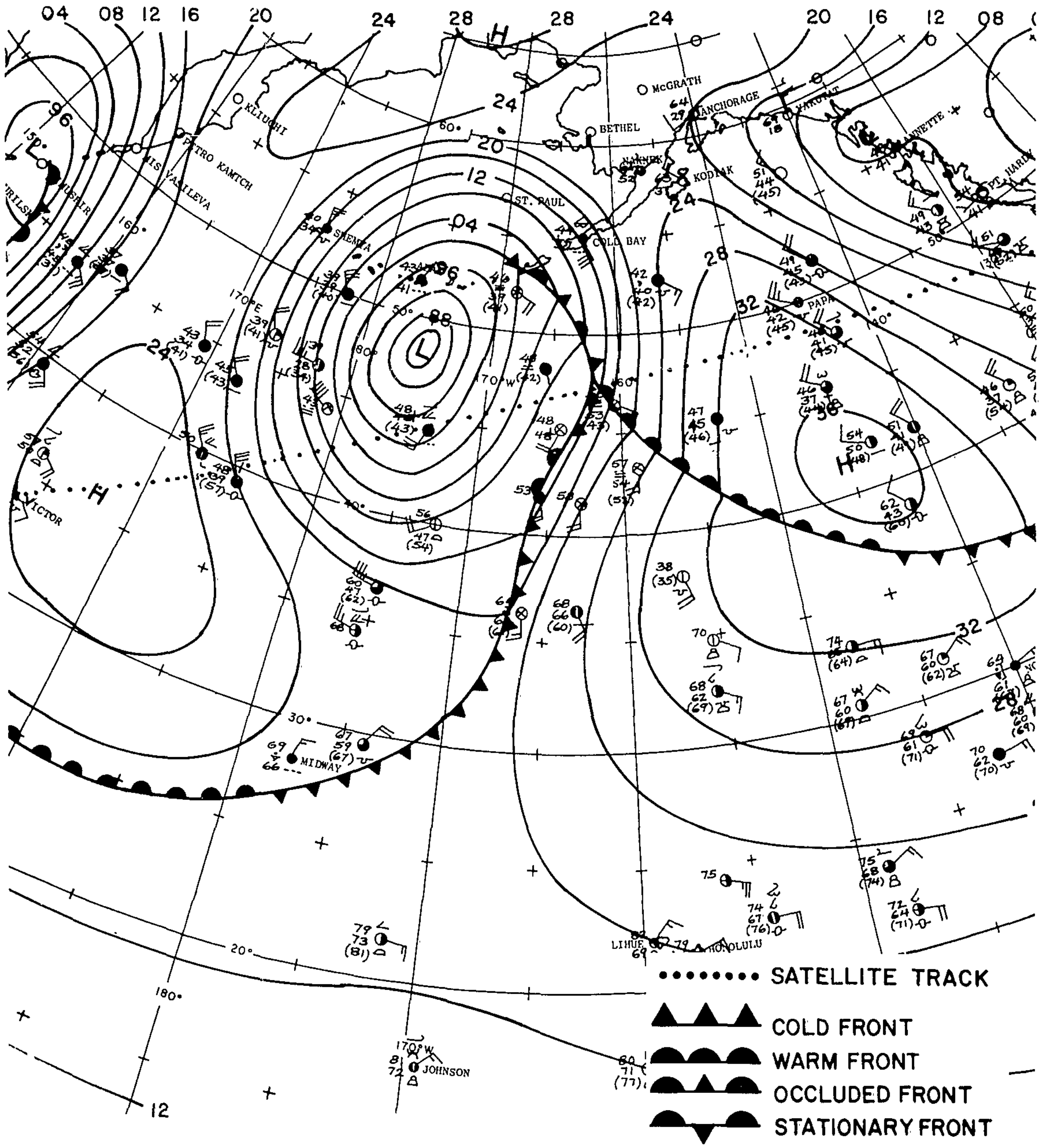


FIG. 19 SURFACE MAP (0000 GMT, 21 May 1960) (From Serebreny, Wiegman and Hadfield 1962)

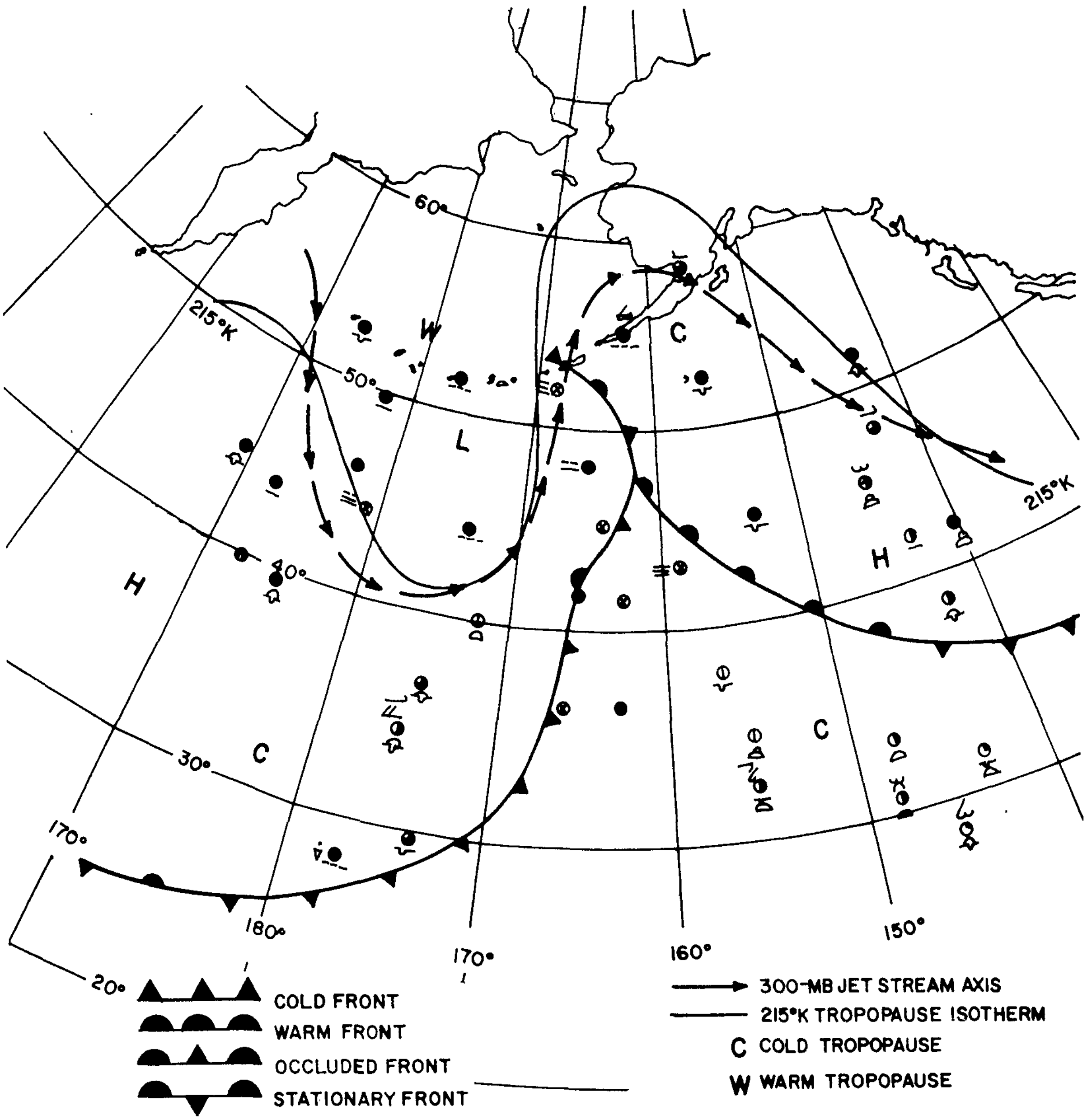


FIG. 20 OVERLAY OF SELECTED SURFACE AND UPPER AIR DATA FOR NORTH PACIFIC EXTRATROPICAL CYCLONE (0000 GMT, 21 May 1960)

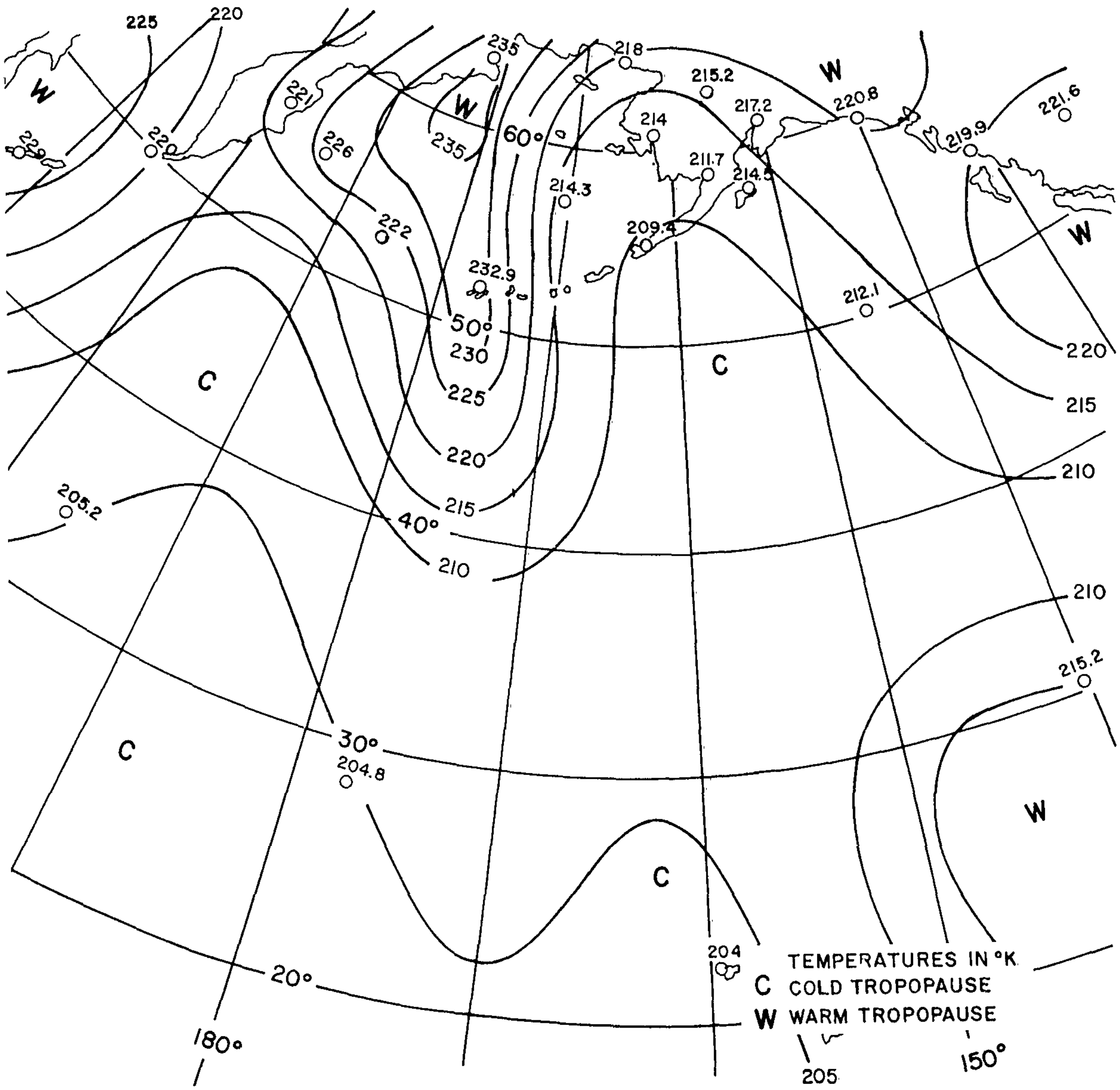


FIG. 21 TROPOPAUSE TEMPERATURE MAP OF NORTH PACIFIC (0000 GMT, 21 May 1960)

overlay of the surface frontal positions, 300-mb jet stream axis, distribution of tropopause temperatures of 215°K or less, and surface observations of clouds from these maps. It may be noted that the overlay (Fig. 20) shows information from Fig. 21; however, the overlay appears first to allow easy comparison of the overlay data with the complete tropopause temperature distribution (Fig. 21).

At the tropopause level, a tongue of tropical air at cold cloud temperatures is seen extending north to Alaska on the right of the poleward-moving jet stream axis. To the west of this cold tongue, warmer tropopause temperatures typical of polar air are noted. Cirriform clouds are reported by only a few surface observers under the tongue of cold tropopause temperatures; however, this seems due to the scarcity of observations and extensive lower clouds obscuring any higher clouds from view. These lower clouds are necessary, though, in our definition of cold clouds. There is also significant probability of dense, cold cirriform clouds along and somewhat to the rear of the surface cold front where it trails out south and west from the tongue of cold tropopause temperatures and where it lies under the cold tropopause (lower left portion of Fig. 20). This is substantiated by surface observations of cirriform clouds, lower opaque clouds and showers reported in the area.

3. Extratropical Cyclone Photographed by TIROS I over Central United States

Figure 22 represents TIROS I satellite photographs of another extratropical cyclone which was extensively studied previously (Timchalk and Hubert, 1961) and which was centered in the central United States. These photographs were taken just a few hours before those just discussed depicting the extratropical cyclone in the Pacific. The jet stream axis over the cyclone is revealed on the accompanying 300-mb map (Fig. 23). Figures 24 and 26 are the surface and tropopause temperature maps of the area, respectively. Figure 25 is an overlay of the same type as shown in the previous example. Again, a tongue of cold tropopause temperatures is noted extending northward on the right of a poleward-moving jet stream to the vicinity of Hudson Bay. Warmer tropopause temperatures of polar air are again observed immediately west of the cold tongue. Note several

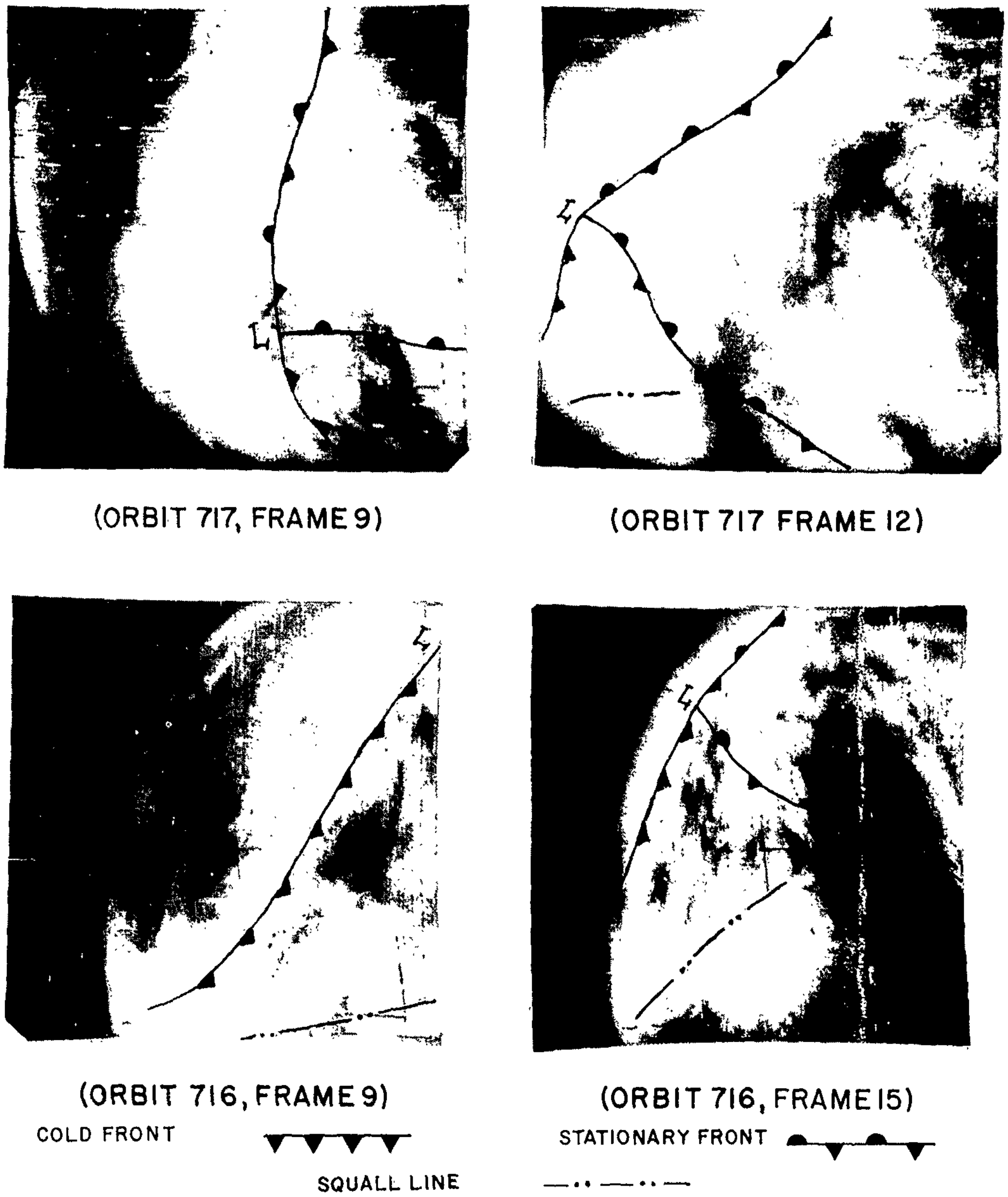


FIG. 22 TIROS I PICTURES OF EXTRATROPICAL CYCLONE IN CENTRAL U.S. WITH SUPERIMPOSED SURFACE ANALYSIS
(1900-2100 GMT, 20 May 1960) (After Timchalk and Hubert, 1961)

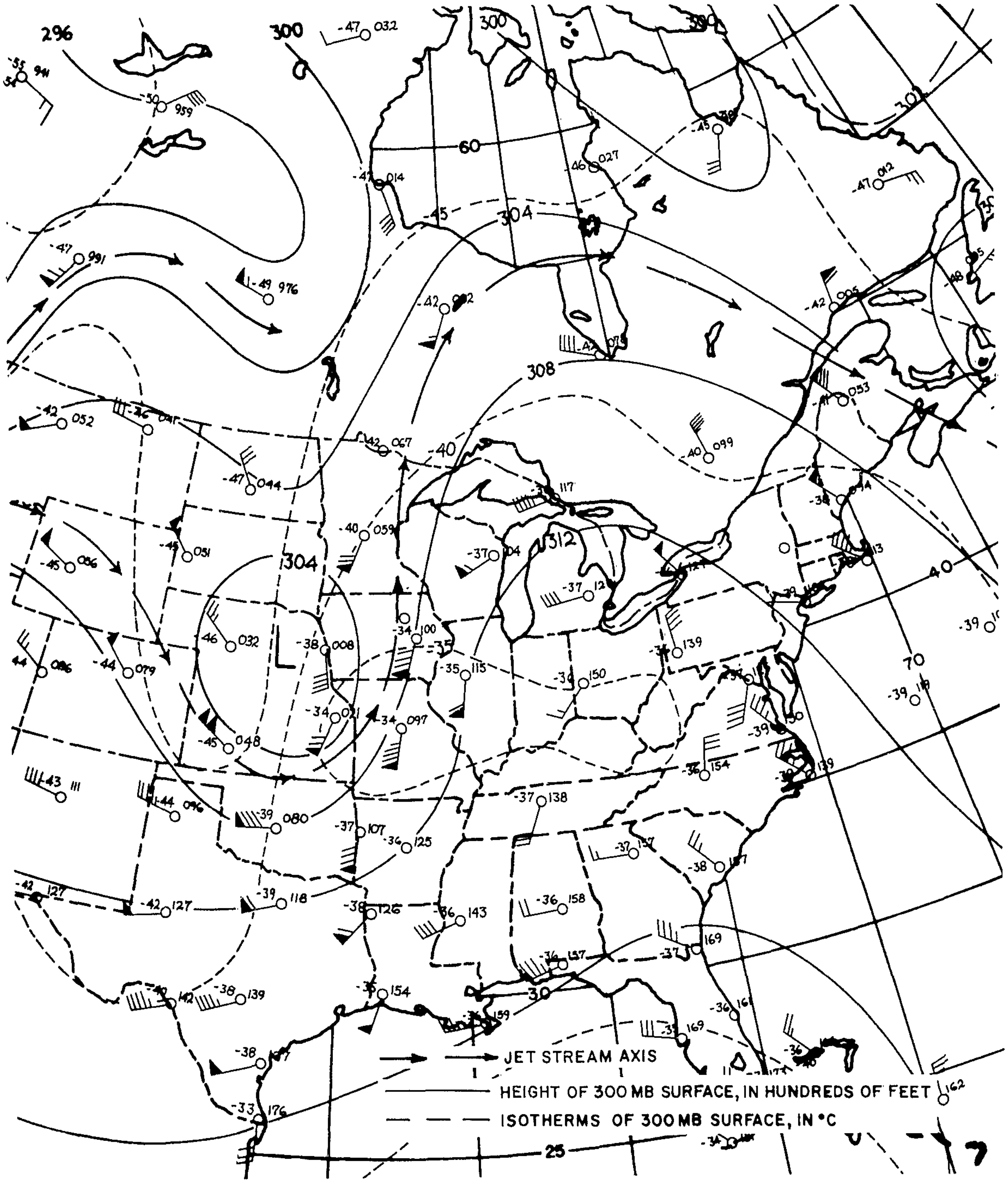


FIG. 23 300 MB MAP (0000 GMT, 21 May 1960)

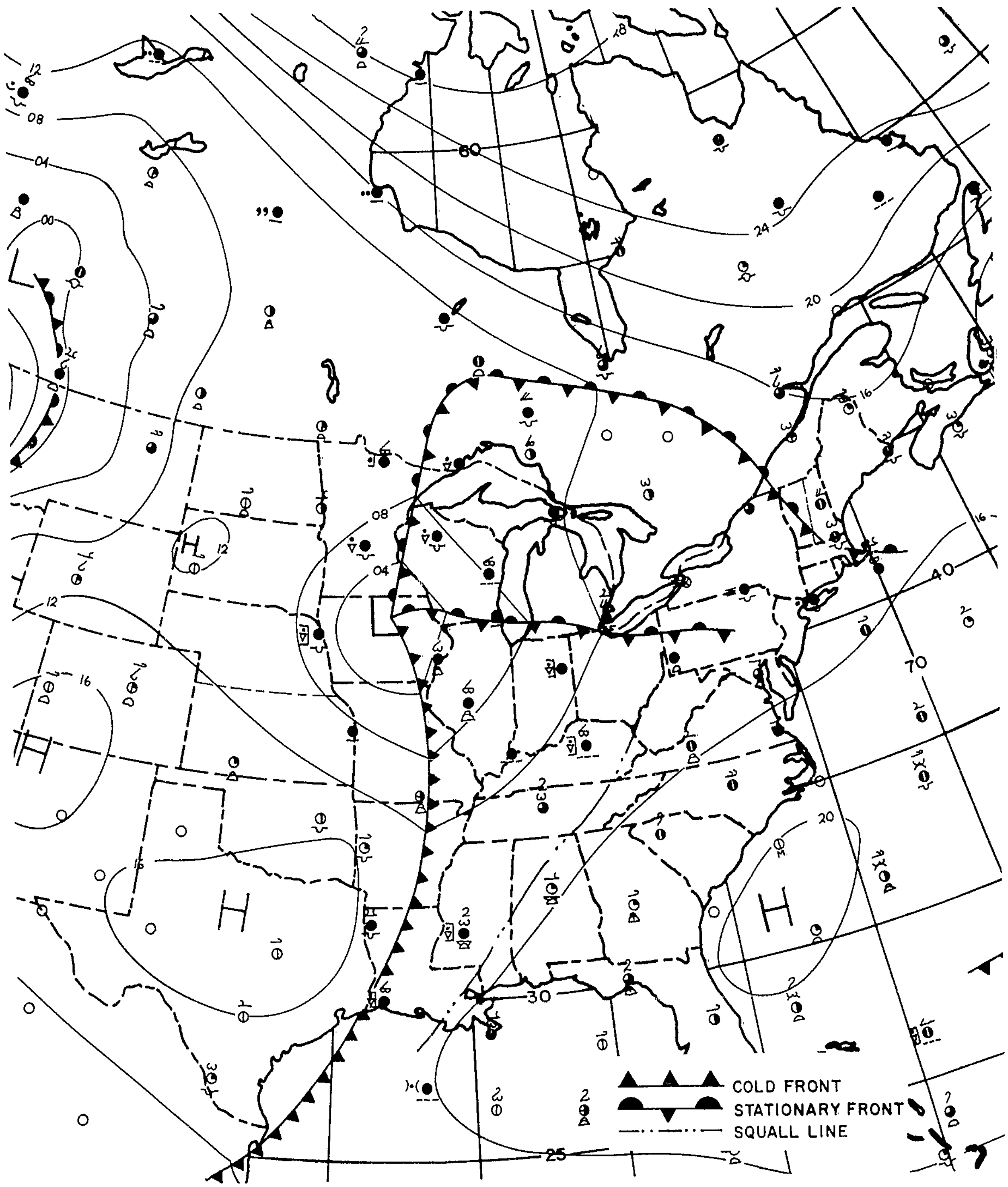


FIG. 24 SURFACE MAP (0000 GMT, 21 May 1960)

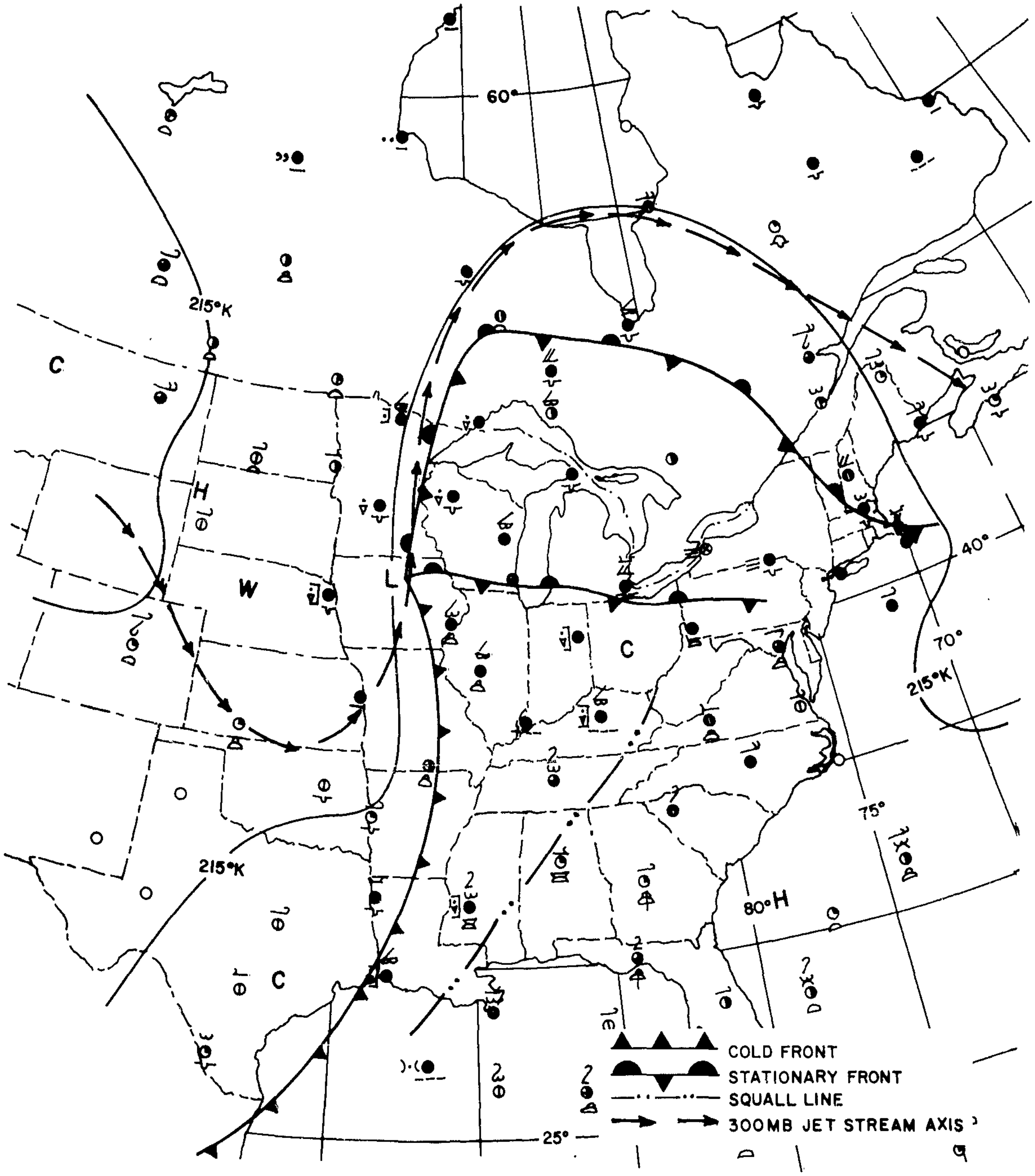


FIG. 25 OVERLAY OF SELECTED SURFACE AND UPPER AIR DATA FOR EXTRATROPICAL CYCLONE IN CENTRAL U.S. (0000 GMT, 21 May 1960)

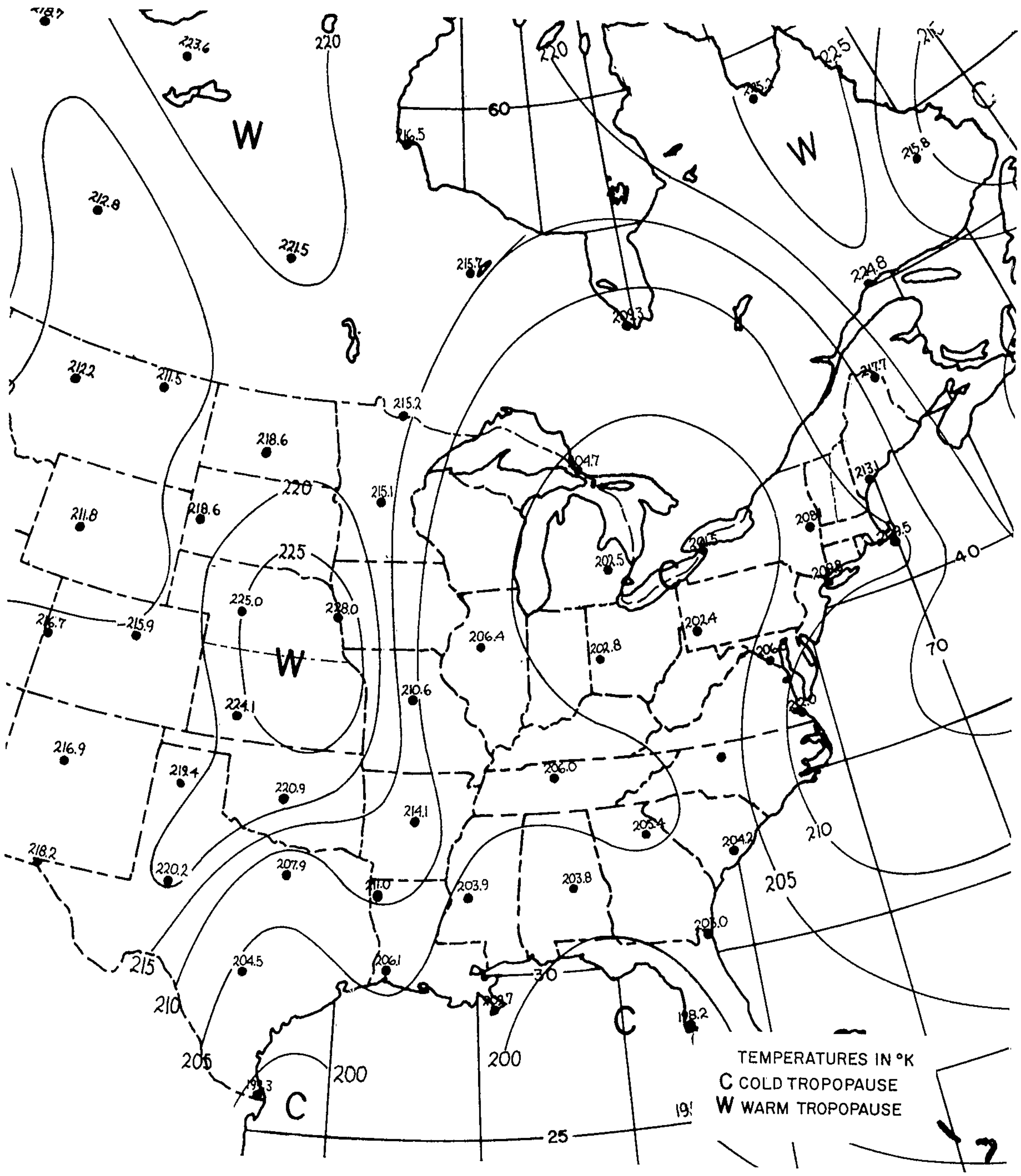


FIG. 26 TROPOPAUSE TEMPERATURE MAP (0000 GMT, 21 May 1960)

surface observations of cirriform clouds, lower opaque clouds and precipitation within the cold tropopause tongue. Another interesting feature associated with this cyclone is a pre-frontal squall line. Thunderstorms along it show up as bright cloud areas in the satellite pictures (Fig. 22). The squall line is a very common occurrence in the central and eastern United States and often forms a nearly continuous band stretching for hundreds of miles in an alignment roughly parallel to and ahead of the surface cold front. Note that the squall line with its line of thunderstorms is within the area of cold tropopause temperatures, and that there are also showers, thunderstorm activity, and cirriform clouds along the trailing cold front where it lies under the cold tropopause.

4. Extratropical Cyclone over Central United States with Associated Squall Line Photographed by U-2

Some impressive pictures of thunderstorm clouds along a squall line were taken from a high-flying U-2 aircraft on 28 May 1962. A sequence of these pictures, shown in Fig. 27 was taken as the U-2 was approaching the line from the west. The squall line was located ahead of a surface cold front associated with another extratropical cyclone in the central United States. (See surface map, Fig. 28). The U.S. Weather Bureau analysis did not indicate the squall line extending into Texas in this map of about two hours later than the photographs. However, thunderstorm clouds were still reported there at the time. Figures 29 and 31 are the associated 300-mb and tropopause temperature maps, respectively. Figure 30 is an overlay of the same type as shown in the two previous examples. A tongue of cold tropopause temperatures again is observed extending northward to the right of a poleward-moving jet stream. Warm tropopause temperatures of polar air are again noted to the west of the cold tongue. The squall line activity as well as several other surface observations of cirriform clouds, lower clouds and precipitation are again indicated within the cold tropopause tongue. Showers, thunderstorm activity and cirriform clouds are also noted along the trailing cold front where it lies below the cold tropopause.

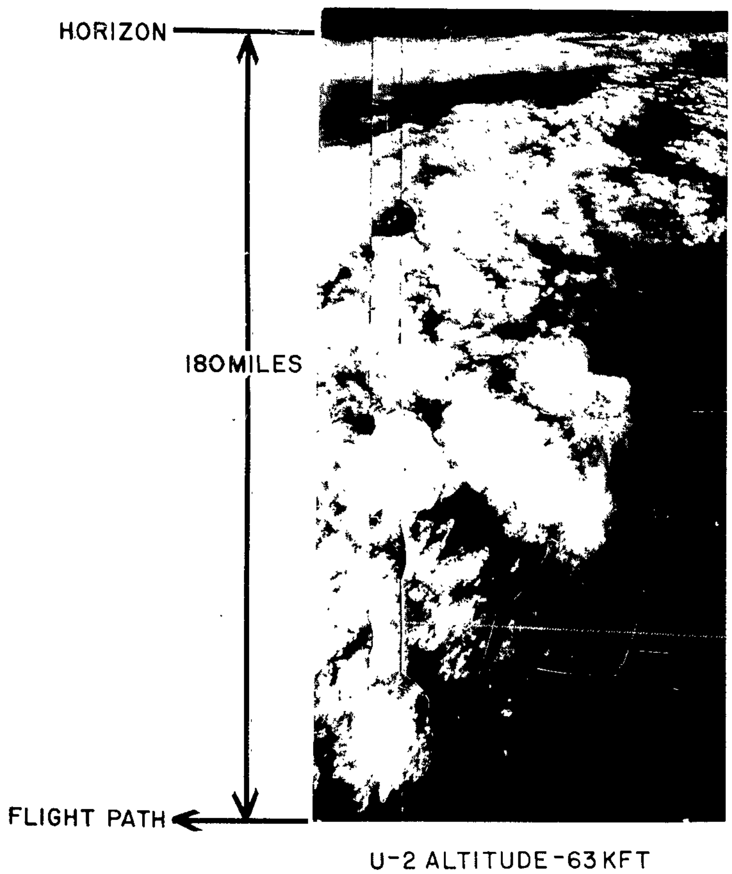


FIG. 27 U-2 PICTURES OF SQUALL LINE ACROSS TEXAS
(2140 GMT, 28 May 1962)

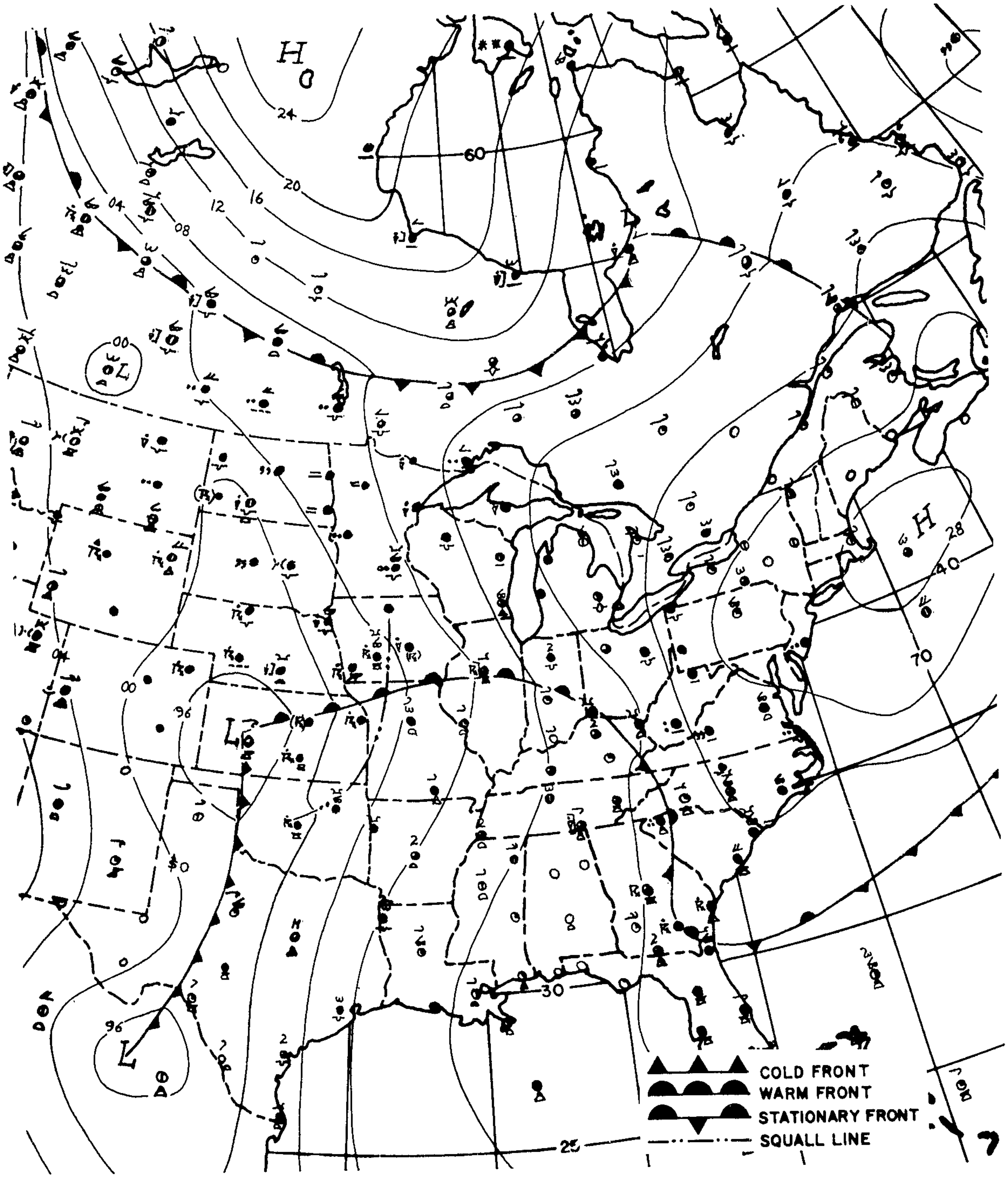


FIG. 28 SURFACE MAP (0000 GMT, 29 May 1962)

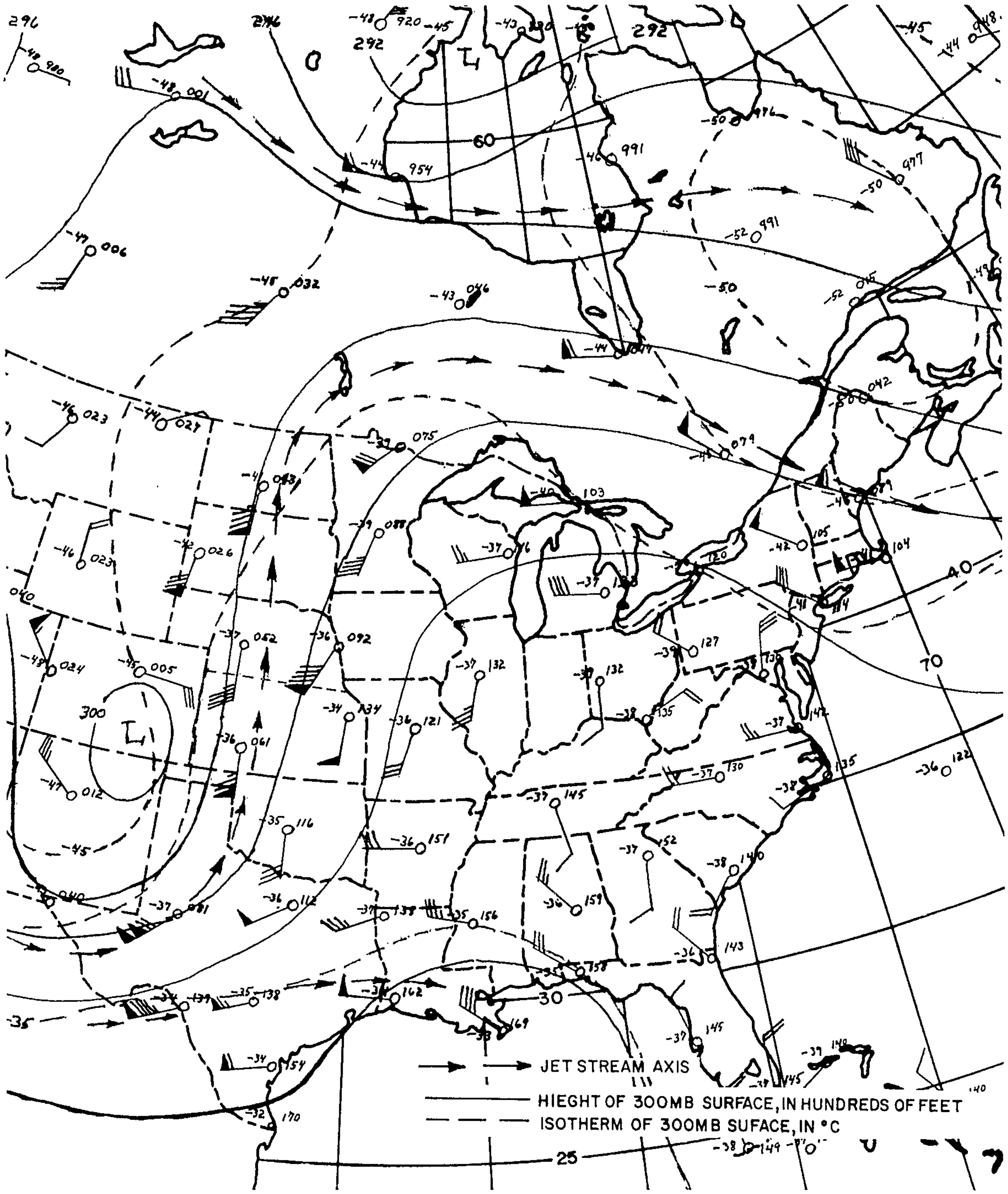


FIG. 29 300 MB MAP (0000 GMT, 29 May, 1962)

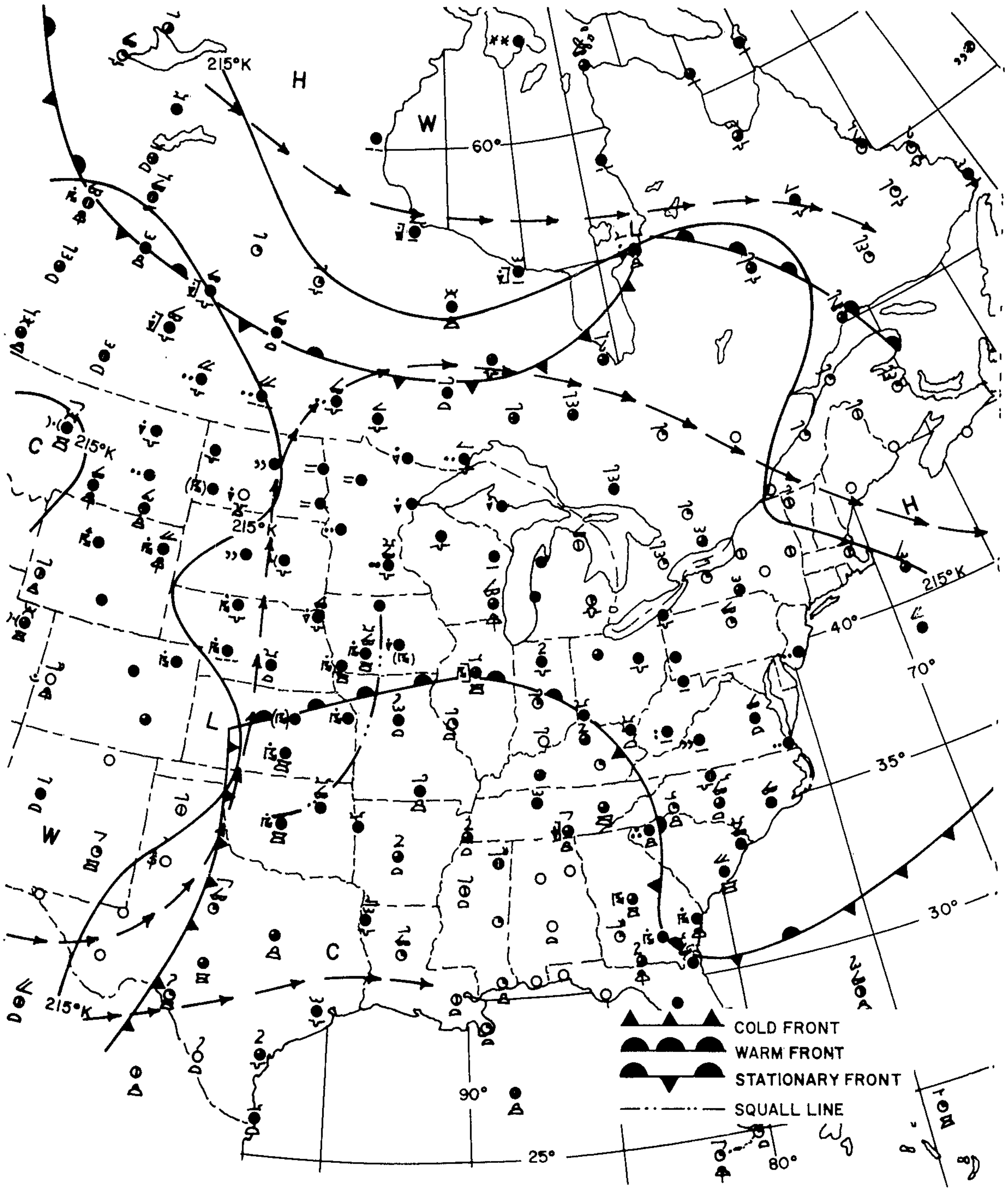


FIG. 30 OVERLAY OF SELECTED SURFACE AND UPPER AIR DATA FOR EXTRATROPICAL CYCLONE IN CENTRAL U.S. (0000 GMT, 29 May 1962)

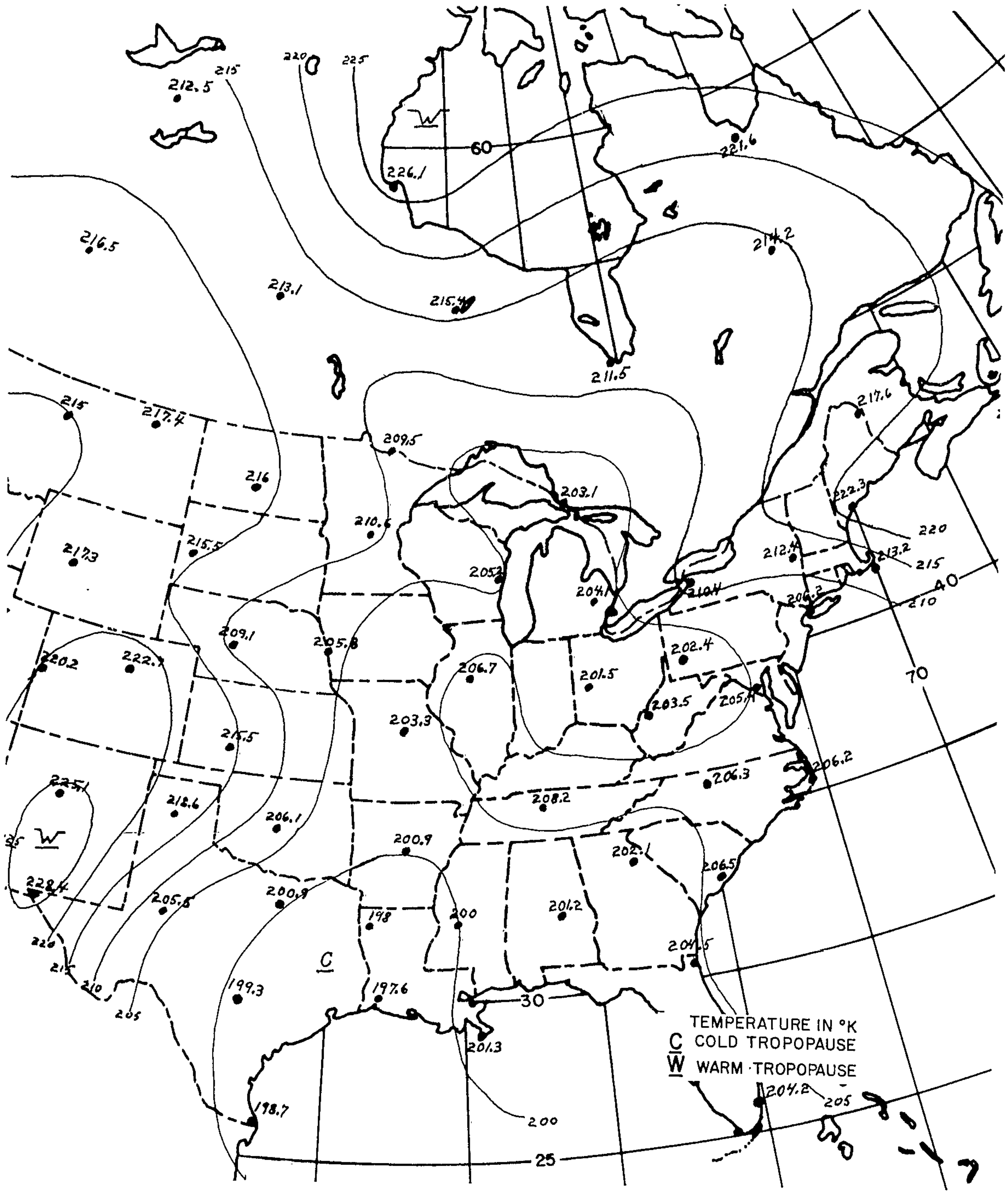


FIG. 31 TROPOPAUSE TEMPERATURE MAP (0000 GMT 29 May 1962)

5. Extratropical Cyclone Viewed by TIROS II Infrared Sensors Over Great Lakes

The fourth extratropical cyclone studied was centered over the Great Lakes when infrared sensors on the TIROS II satellite scanned over it at 1100 GMT, 29 November 1960. Figures 32, 33, and 35 represent the 300-mb, surface and tropopause temperature maps, respectively, over the area on 1200 GMT, 29 November 1960. Figure 34 is an overlay similar to those of the previous examples, except that isopleths of equivalent blackbody radiating temperatures (^{0}K) in the 8-12 micron atmospheric window region (See Fig. 1) have also been added. It may be recalled that most currently operational infrared horizon sensors are sensitive in this wavelength region and that cold clouds are a significant problem to these sensors.

A tongue of cold tropopause temperatures is again observed extending northward to the right of a poleward-moving jet stream, with a projection of these cold tropopause temperatures westward over the occluded portion of the cyclone. Warm tropopause temperatures of polar air are noted again to the west of the cold tongue, and several observations of cirri-form clouds, lower opaque clouds and occasional precipitation are also indicated within the cold tongue, where conditions appear favorable for cold cloud occurrence. This last statement is supported by the infrared data on the overlay (Fig. 34), which indicates the areas of lowest radiating temperatures are within the cold tropopause tongue. However, the lowest radiating temperatures measured by the satellite are about 20^{0}K warmer than the indicated tropopause temperatures. This discrepancy is probably due to the highest clouds occurring a few thousand feet below the tropopause or the satellite infrared sensors viewing non-uniformly dense layers of cirriform and lower clouds. In the latter case, warmer infrared radiation from lower levels would be mixed in with the cirriform cloud return.

6. General Model of Area Favorable for Cold Clouds Associated with An Occluding Extratropical Cyclone

Certain similarities are noted in the examples just studied. A jet stream moving poleward is associated with an active extratropical

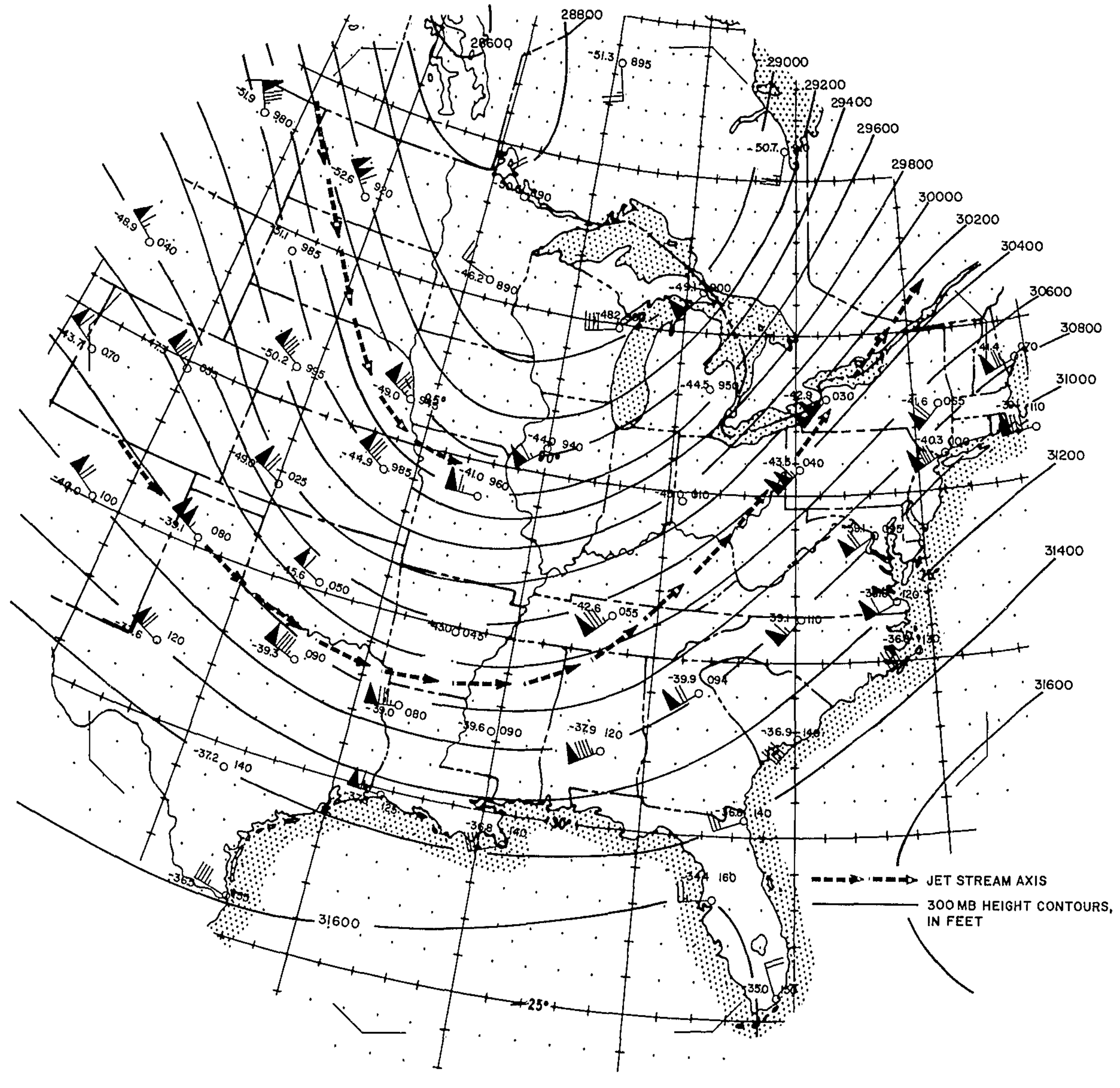


FIG. 32 300 MB MAP (1200 GMT, 29 November 1960)

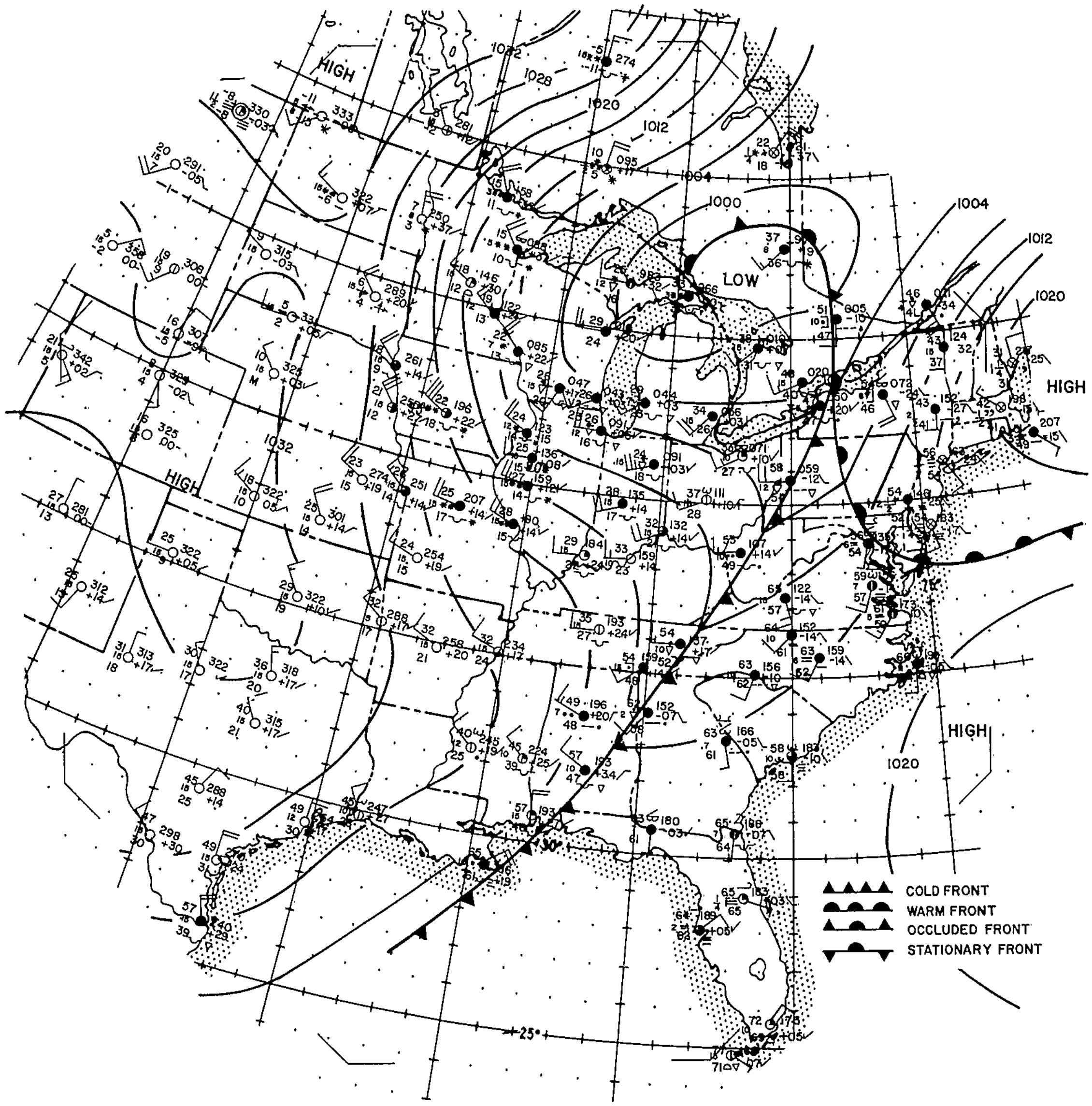


FIG. 33 SURFACE MAP (1200 GMT, 29 November 1960)

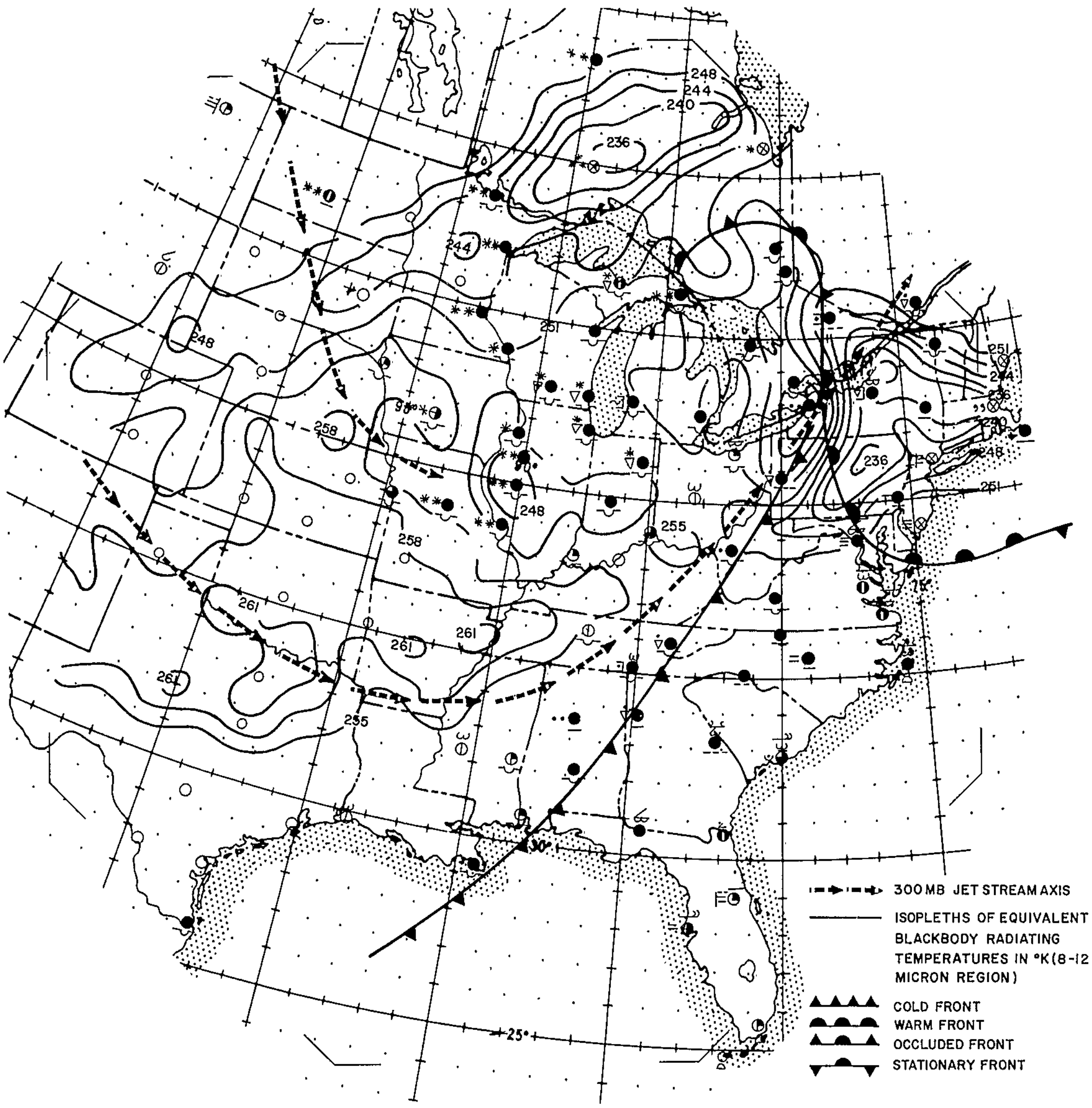


FIG. 34 OVERLAY OF SELECTED SURFACE, UPPER AIR AND INFRARED DATA FOR EXTRATROPICAL CYCLONE OVER GREAT LAKES (1100-1200 GMT, 29 November 1960)

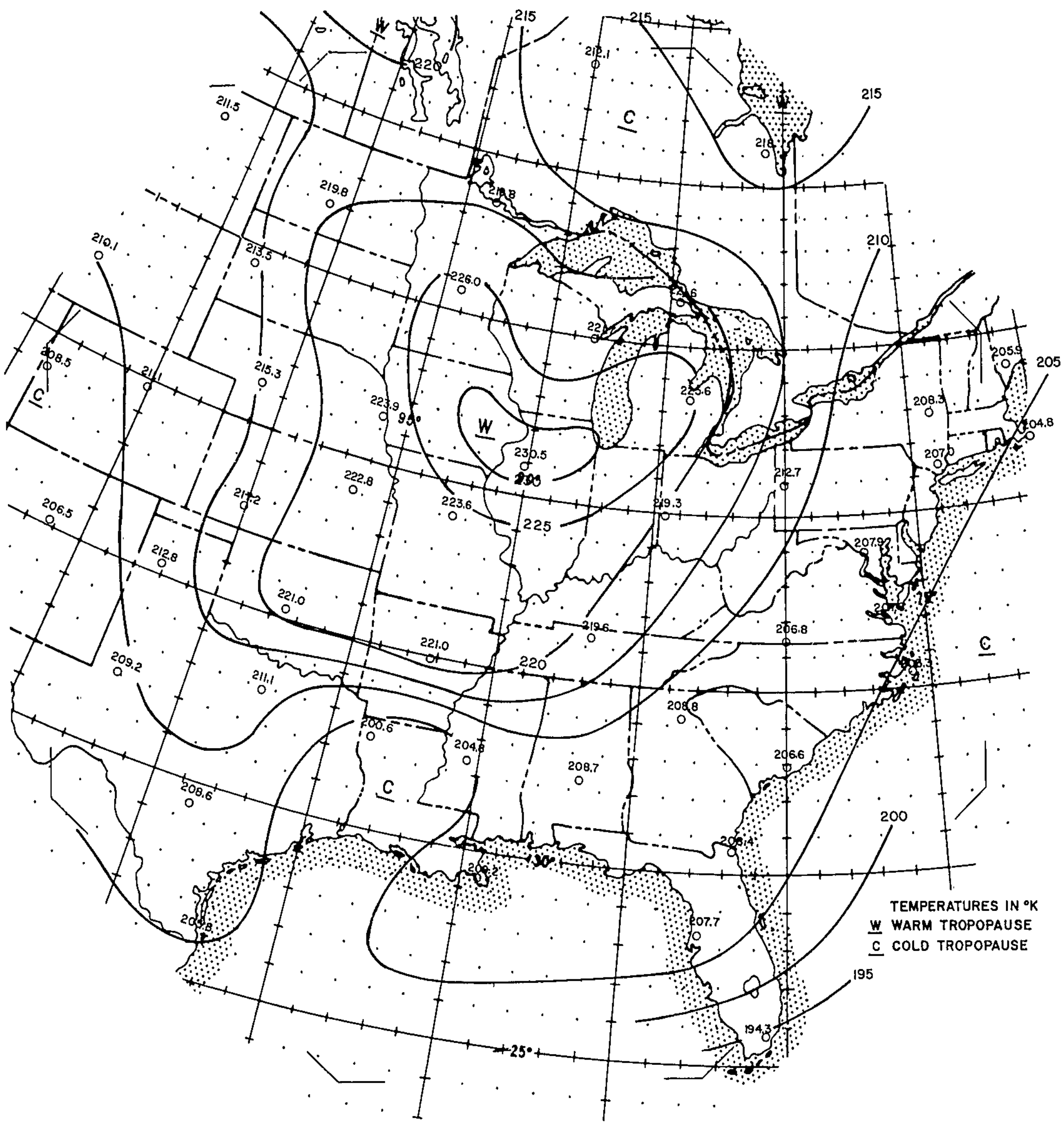


FIG. 35 TROPOPAUSE TEMPERATURE MAP (1200 GMT, 29 November 1960)

cyclone and occurs along the left boundary (in the northern hemisphere) of a poleward-moving tongue of tropical air with its cold tropopause. This tongue of cold tropopause temperatures outlines an area where conditions are favorable for occurrence of cold clouds. Also, conditions are favorable for cold clouds to occur with pre-frontal weather activity such as squall lines farther equatorward in the warm sector of the cyclone between the cold and warm fronts. Cold clouds are also probable along and somewhat to the rear of the trailing surface cold front where it lies under the cold tropopause. Figure 36 reflects these statements in a general model of the area favorable for cold clouds associated with an occluding extratropical cyclone. The length and width of the poleward-extending cold tropopause tongue may be as much as 20-30° latitude and longitude, respectively, with any variation mainly influenced by the degree of meridional flow and the steepness of the slopes of the polar air mass along the cyclonic wave.

7. Longitudinal Frequencies of Poleward-Extending Areas Favorable for Cold Clouds Associated with Extratropical Cyclones

Since a poleward-moving jet stream associated with an extratropical cyclone in the middle latitudes is indicative of a tongue of tropical air favorable for cold clouds extending poleward, a study of the frequency distribution of such jet streams in the northern hemisphere should provide a measure of the frequency distribution of areas favorable for cold clouds being projected poleward in the middle latitudes of the northern hemisphere. The results of such a study are shown in Fig. 37 in the form of average monthly frequency distributions of poleward-moving jet streams as a function of longitude for the northern hemisphere. The data sources for the study were five-year compilations, over a ten-year period, of monthly and seasonal jet-stream occurrences at and north of 50° latitude at the 500-mb level for the northern hemisphere (Serebreny, Wiegman and Hadfield, 1957, 1958). Noteworthy in these distributions are the consistent relatively greater frequencies, particularly in the fall, winter and spring months, in the 0-60°W and 120°W-160°E longitude regions. These zones correspond to the two major regions of stagnation of extratropical cyclones in the northern hemisphere. Figure 38 illustrates

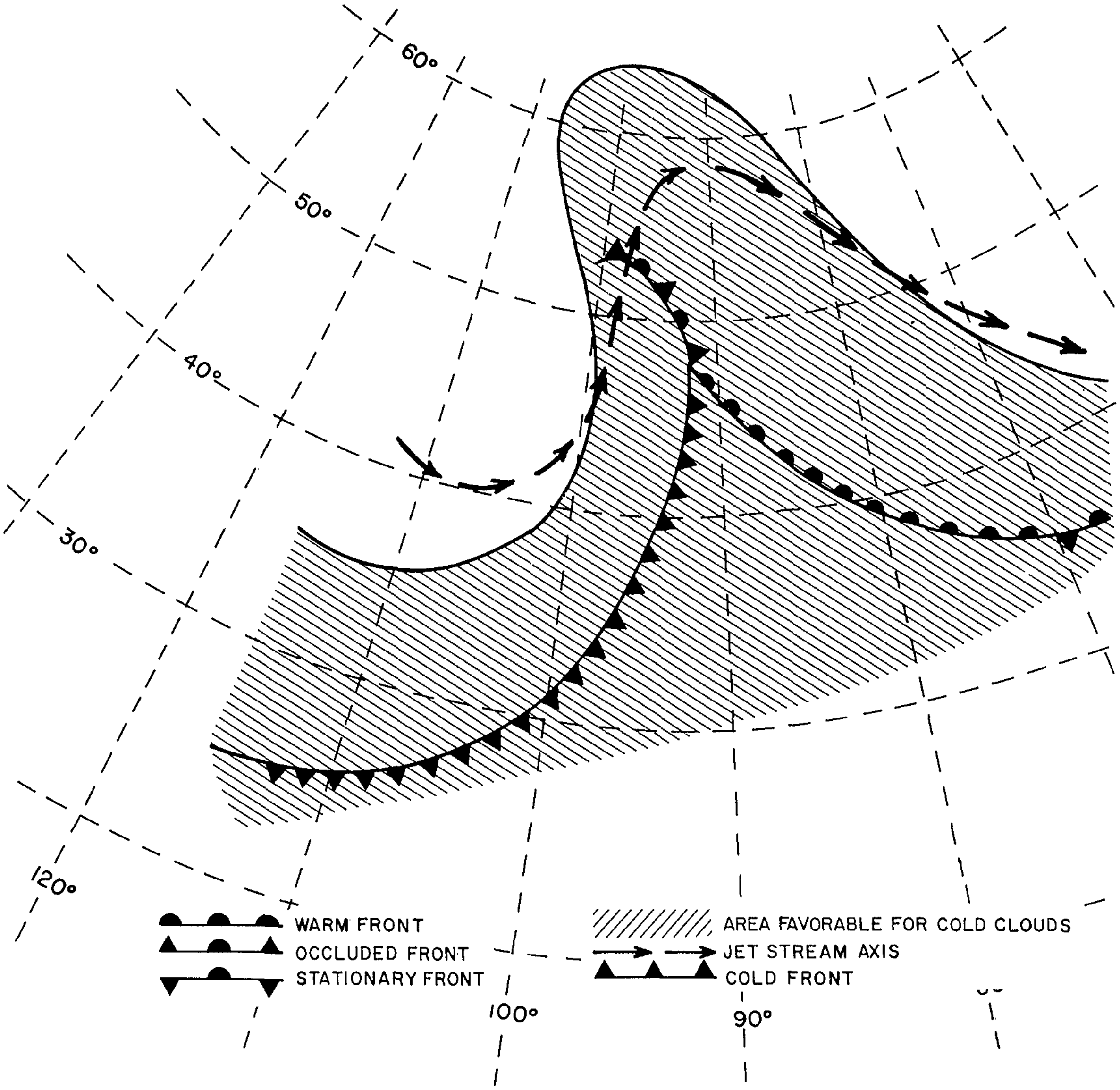


FIG. 36 GENERAL MODEL OF AREA FAVORABLE FOR COLD CLOUDS ASSOCIATED WITH AN OCCLUDING EXTRATROPICAL CYCLONE

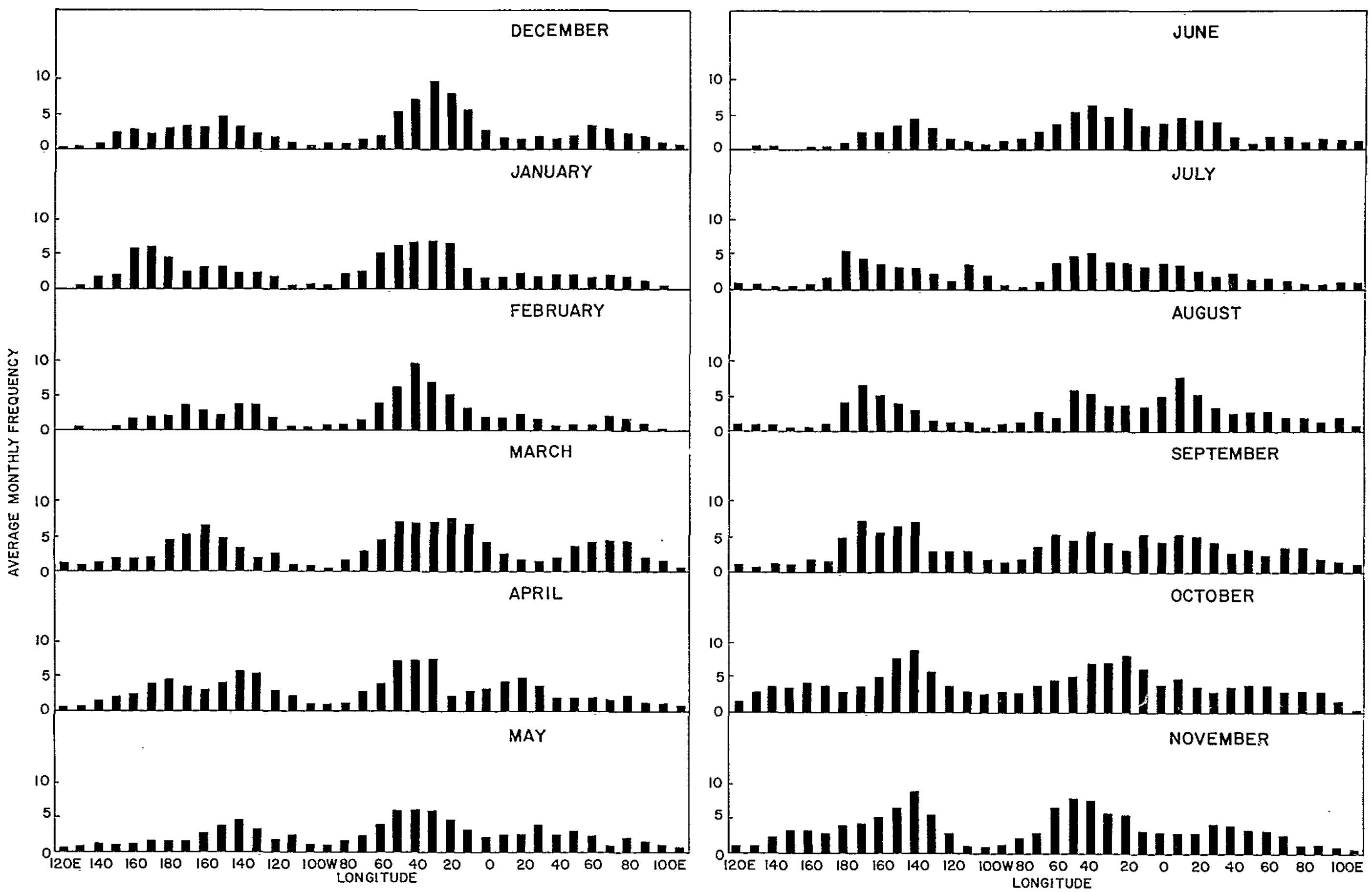


FIG. 37 AVERAGE MONTHLY FREQUENCY DISTRIBUTIONS OF POLEWARD-MOVING JET STREAMS IN NORTHERN MIDDLE LATITUDES (After Serebreny, Wiegman and Hadfield, 1957, 1958)

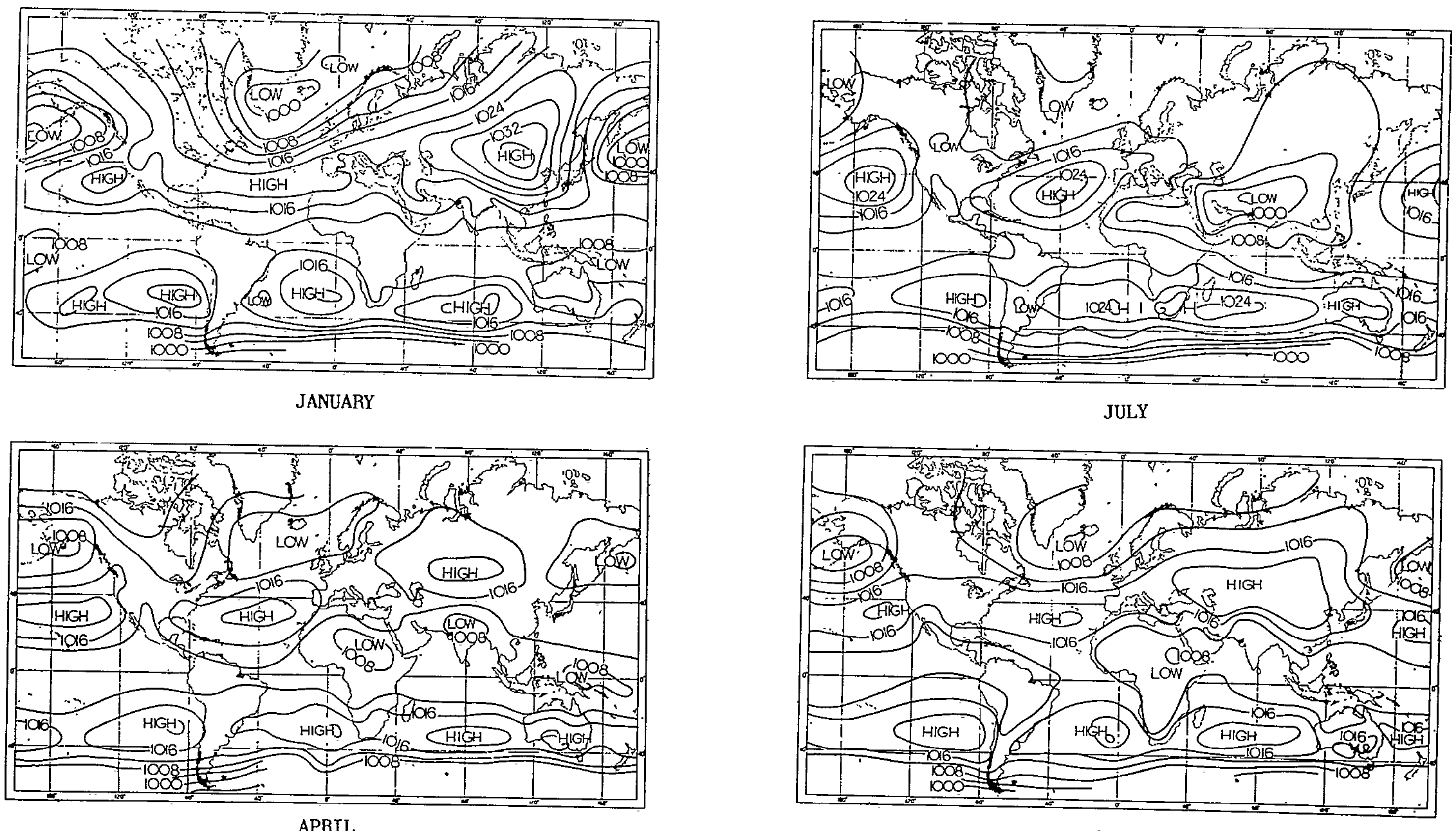


FIG. 38 MEAN SEA-LEVEL PRESSURE DURING THE MID-SEASON MONTHS (From Bannon, 1953)

these regions. In the southern hemisphere, the pressure distribution in the middle latitudes is not well known, but it appears that a more or less continuous belt of general low pressure exists south of 40° latitude (See Fig. 38). Such a pressure pattern should result in a more uniform distribution of poleward-moving jet streams and associated poleward projections of tropical air favorable for cold clouds as a function of longitude than indicated in Fig. 37 for the northern hemisphere.

V SUMMARY AND CONCLUSIONS

Currently operational infrared horizon sensors are having difficulty with cold clouds because they are sensitive to earth radiation in those wavelengths that are transmitted through the atmosphere with little or no absorption. Thus a sensor of this type detects a sharp change in radiation intensity similar to that at the earth-space boundary when its field-of-view passes across the boundary between warm, cloud-free earth and a cold cloud. Future sensors are being designed to be sensitive to longer wavelength radiation, which is greatly absorbed by the atmosphere. Such a sensor will experience very little change in radiation intensity as its field-of-view sweeps across the boundary between cloud-free earth and a cold cloud. The new sensors may solve the cold cloud problem, but at this point, there are still some uncertainties in their design and development. In case the new sensors are not successful and the earlier designs have to be relied upon, the results of a study such as this would prove useful in operational programming of satellites, to help cope with the problem.

Clouds that affect horizon sensors are dense cirriform clouds occurring near the tropopause of a tropical air mass where the temperature is on the order of $200^{\circ}K$. To appear really cold to an infrared sensor, these cirriform clouds must be associated with lower opaque clouds.

Investigation of horizon sensor geometry shows that the first degree or two below the horizon encompasses a considerably wider area on the earth than the same angular field-of-view several degrees below the horizon. Also the minimum width of a band of cold clouds corresponding to a particular angular error in horizon location increases as the orbital altitude of the satellite increases. The portion of the earth visible from a satellite also increases as the orbital altitude increases.

The magnitudes of these areas viewed over long distances by a satellite indicate that extended cloud systems associated with meso- or synoptic-scale weather disturbances, rather than individual cloud elements, are most likely to affect the sensors significantly. These disturbances may be in the form of an active Intertropical Convergence Zone (ITCZ), monsoons, tropical cyclones, and extratropical cyclones in the middle latitudes of both the northern and southern hemispheres. The distribution of these various weather disturbances over the earth provides a measure of distribution of areas favorable for cold cloud occurrence.

The ITCZ, which is along the boundary near the equator between the trade winds of the northern and southern hemisphere, has only intermittent weather disturbances along it. The zone migrates, on the average, about 15^{o} north and south of the equator in some places as it follows the summer season.

Major monsoon regions are located in Central Africa, India, Southeast Asia, Northeast South America, and Australia.. They are active in the summer months of these areas.

Tropical cyclones are associated with preferred source regions, seasons and paths. They originate in the tropics but may eventually reach the middle latitudes. Their source regions are located in the Central Atlantic and Caribbean area, the Central Pacific area off Southeast Asia, the Central Pacific area off the west coast of Mexico, the South Pacific area east of Australia and New Zealand, the North Indian Ocean in the Bay of Bengal, the North Indian Ocean in the Arabian Sea, the South Indian Ocean to the east of Madagascar and the South Indian Ocean off the northwest coast of Australia. The preferred seasons are the summer and fall months in the various source regions. The size of tropical cyclones can vary from about 100-1000 nm. in diameter.

Extratropical cyclones result in frequent poleward invasions of tropical air to high latitudes. As the jet stream, which is a region of strong winds along the boundary between the tropical and polar air near the tropopause, moves poleward over the surface position of an extratropical cyclone, a tongue of tropical air with its cold tropopause is transported poleward on the right side of the jet stream. In the case of a young cyclone, the tongue extends poleward mainly over the warm front portion. Later, as the cyclone matures and becomes occluded, the tongue not only extends poleward over the warm front, but also circles cyclonically back over the occluded portion. The length and width of the poleward-extending area favorable for cold clouds may be as much as 20-30° of latitude and longitude, respectively.

Since poleward-moving jet streams are indicative of poleward transport of tropical air favorable for cold cloud occurrence, a study was made of the monthly frequency distribution of poleward-moving jet streams in the northern hemisphere. The results of this study indicate that tongues of tropical air favorable for cold clouds project poleward more frequently in the 0-60°W and 120°W-160°E longitude regions in the high northern latitudes. These zones correspond to the two major regions of stagnation of extratropical cyclones in the northern hemisphere. In the southern hemisphere, a more uniform longitudinal distribution of poleward-moving jet streams and associated poleward projections of areas favorable for cold clouds is due to a more or less continuous belt of low pressure in the middle latitudes.

Based on the distributions of areas favorable for cold clouds revealed in this study, errors in infrared horizon sensing due to cold clouds should be temporary, but recurring, for most satellite orbits. This is due to the worldwide preferred locations of cold clouds and the generally high ground speed of satellites.

For example, a satellite might be in a 500 nm polar orbit and have forward- and rearward-looking horizon sensors. As it passed over the north pole its forward-looking sensor might detect the poleward edge of an area of cold clouds near 60° latitude associated with an extratropical cyclone. The rearward-looking sensor probably would not be troubled with cold clouds, as its view would be moving poleward over polar and arctic air above 60° latitude.

As the satellite progressed equatorward, the cold cloud area could continue advancing toward the satellite so that the forward-looking sensor would believe the earth-space interface was at an increasing angular distance below the actual earth-space boundary. The erroneous signal from the forward sensor would upset the satellite vertical alignment even though the rearward sensor might be viewing the actual earth-space boundary near the pole. In the extreme case, this misalignment could continue until a cold cloud area some 20^0-30^0 latitude in length had passed across the view of the sensor. For a satellite at 500 nm orbital altitude, it is estimated that the sensor might view such an area for 5-10 minutes. During this time, any photographs taken would be off-centered. After the view of the forward-looking sensor had passed beyond this cold cloud area, the satellite vertical alignment could be corrected as both forward and rearward sensors viewed the true earth-space boundary. At that time the satellite should be passing over approximately 60^0 latitude. As it continued on equatorward, the forward sensor could start detecting cold clouds associated with the ITCZ and start upsetting the vertical alignment again when the satellite was passing over about 45^0 latitude. Shortly thereafter, the rearward-looking sensor might also start viewing the cold clouds associated with the extratropical cyclone previously passed over by the satellite. The band of cold clouds and weather along the ITCZ can be up to several hundred miles wide, so the forward-looking sensor could be affected by it for a minute or two. However, the rearward-looking sensor might be affected by the cold clouds of the extratropical cyclone to the north until about the time the satellite passed over the equator. Shortly thereafter, the forward-looking sensor could start detecting cold clouds associated with an extratropical cyclone in the southern hemisphere.

And so on around the earth, the satellite could be temporarily misaligned and corrected in a recurring manner as its position in orbit brought into view the various distributions of cold clouds over the earth. Such a situation is not conducive to accurate photographic work; however, either the new sensor designs may solve the cold cloud problem or the programming of picture-taking may be geared to a knowledge of the location of the satellite at any time with respect to the location of areas of high probability of cold clouds.

REFERENCES

Klass, P. J., 1962: "Cold Clouds Troubling Horizon Sensors," Aviation Week and Space Technology, October 1, 1962, pp. 50-64.

Hanel, R. A., Bandeen, W. R., and Conrath, B. J., 1962: "The Infrared Horizon of the Planet Earth," NASA Report X-650-62-164, August 1962, 20 pp.

Goldie, N., Moore, J. G., and Austin, E. E., 1958: "Upper Air Temperature Over the World," Geophysical Memoirs No. 101, Meteor. Office, Great Britain, 228 pp.

Serebreny, S. M., Wiegman, E. J., and Hadfield, R. G., 1962: "Investigation of the Operational Use of Cloud Photographs from Weather Satellites in the North Pacific," Final Report under U.S. Weather Bureau Contract Cwb 10238, Stanford Research Institute, Menlo Park, California, 93 pp.

Byers, H. R., 1959: General Meteorology, McGraw-Hill Book Co., Inc., 540 pp.

Dunn, G. E., and Miller, B. I., 1960: Atlantic Hurricanes, Louisiana State University Press, 326 pp.

Hubert, T. F., and Berg, O., 1955: "A Rocket Portrait of a Tropical Storm," Monthly Weather Review, Vol. 83, No. 6, pp. 119-124.

Bergeron, J., 1951: "General Survey in the Field of Cloud Physics," International Union of Geodesy and Geophysics, Assoc. Meteor., Ninth General Assembly Memoirs, Brussels, pp. 120-134.

Timchalk, A., and Hubert, T. F., 1961: "Satellite Pictures and Meteorological Analysis of a Developing Low in the Central United States," Monthly Weather Review, Vol. 89, No. 11, pp. 429-445.

Goddard Space Flight Center, 1961: TIROS II Radiation Data Catalog, Vol. 1, 355 pp.

Goddard Space Flight Center, 1961: TIROS II Radiation Data Users Manual, 57 pp.

Serebreny, S. M., Wiegman, E. J., and Hadfield, R. G., 1957: "A Study of Jet Stream Conditions in the Northern Hemisphere During Winter," Technical Report No. 5, Meteorology Dept., Pan American World Airways, Inc., 122 pp.

Serebreny, S. M., Wiegman, E. J., and Hadfield, R. G., 1957: "A Study of Jet Stream Conditions in the Northern Hemisphere During Summer," Technical Report No. 6, Meteorology Dept., Pan American World Airways, Inc., 111 pp.

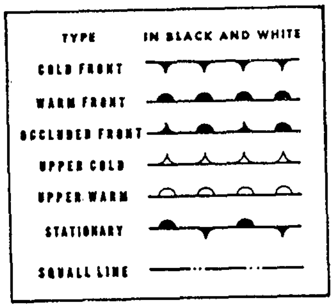
Serebreny, S. M., Wiegman, E. J., and Hadfield, R. G., 1958: "A Study of Jet Stream Conditions in the Northern Hemisphere During Spring," Technical Report No. 7, Meteorology Dept., Pan American World Airways, Inc., 96 pp.

Serebreny, S. M., Wiegman, E. J., and Hadfield, R. G., 1958: "A Study of Jet Stream Conditions in the Northern Hemisphere During Fall," Technical Report No. 8, Meteorology Dept., Pan American World Airways, Inc., 87 pp.

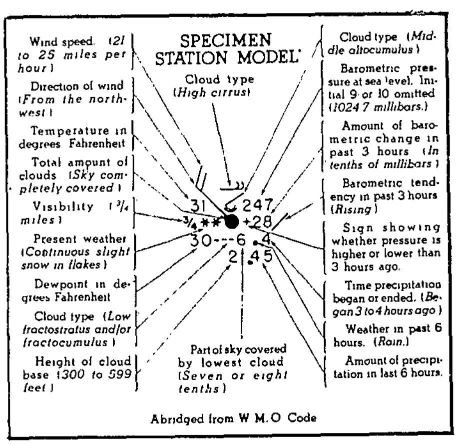
Bannon, J. K., 1953: "Some Aspects of the Mean Upper-Air Flow over the Earth," Proc. of the Toronto Meteorological Conference, 1953, Published by the American and Royal Meteorological Societies, pp. 109-121.

APPENDIX A – PLOTTING MODELS AND CODE FORMS

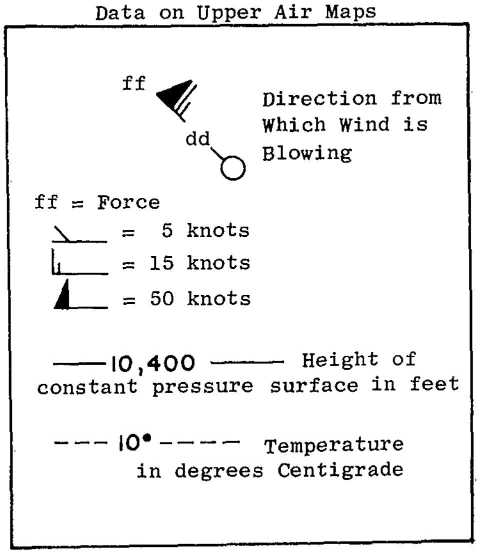
A. Code for Depiction of Fronts on Surface Maps



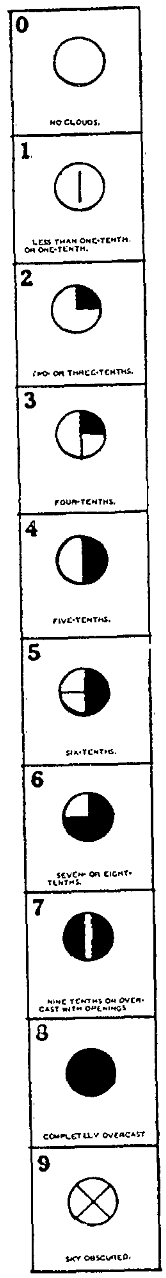
B. Plotting Model for Data on Surface Weather Charts



C. Plotting Model for Wind Data on Upper Air Maps

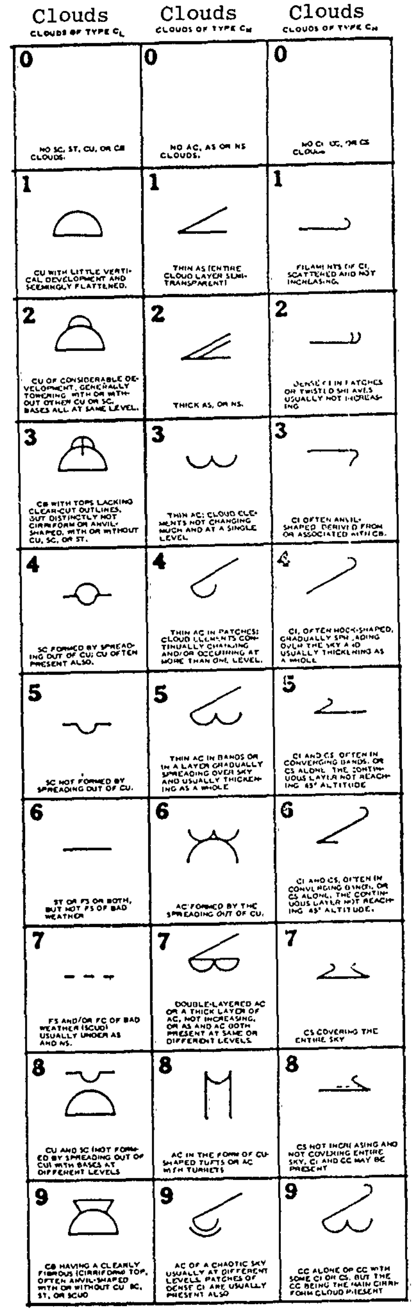


D. Code Form for Total Cloud Cover

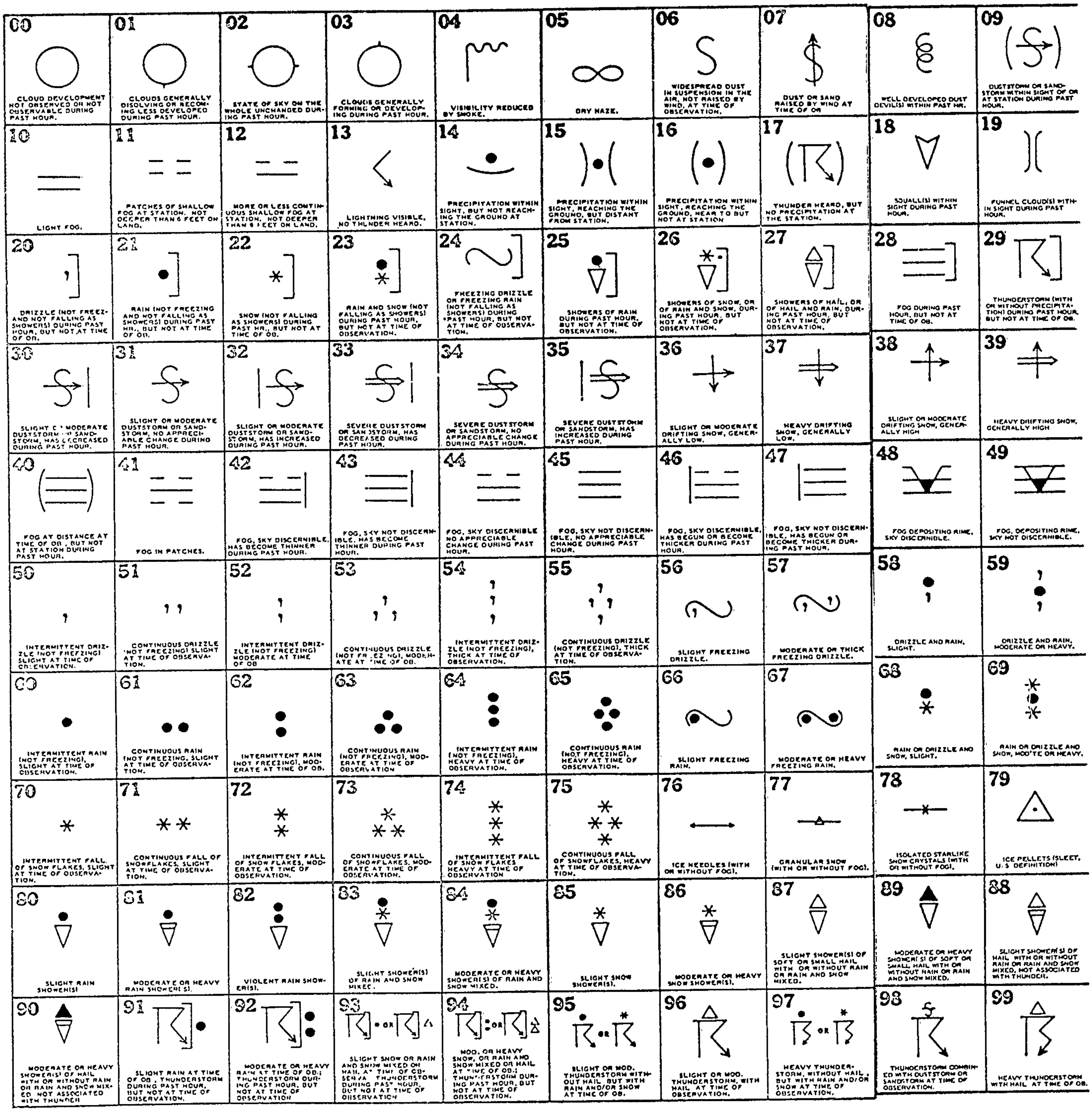


E. Code Forms for Cloud Types

Low Clouds | Middle Clouds | High Clouds



F. CODE FORMS FOR INDICATING PRESENT WEATHER ON SURFACE WEATHER MAPS



UNCLASSIFIED

AF Cambridge Research Laboratories, Bedford, Mass. Meteorological Development Laboratory
A METEOROLOGICAL STUDY OF COLD CLOUDS AS RELATED TO SATELLITE INFRARED HORIZON SENSORS, by J. E. Alder, February 1963. 64 pp.
AFCRL-63-413 Unclassified report

This report discusses meteorological aspects of cold clouds that affect infrared horizon sensors of satellites. Conditions favorable for the occurrence of cold clouds are described and the distribution of areas favorable for cold clouds over the earth are discussed. Particular emphasis is placed on the possibilities for cold clouds associated with an extratropical cyclone. Specific examples of this type of storm are studied, including one that was viewed by the infrared sensors of TIROS II. A model is formulated showing an area favorable for cold clouds in an occluding extratropical cyclone.

1. Meteorology
2. Cold Clouds
3. Satellite Infrared Horizon Sensors

I. Alder, J. E.

UNCLASSIFIED

UNCLASSIFIED

AF Cambridge Research Laboratories, Bedford, Mass. Meteorological Development Laboratory
A METEOROLOGICAL STUDY OF COLD CLOUDS AS RELATED TO SATELLITE INFRARED HORIZON SENSORS, by J. E. Alder, February 1963. 64 pp.
AFCRL-63-413 Unclassified report

This report discusses meteorological aspects of cold clouds that affect infrared horizon sensors of satellites. Conditions favorable for the occurrence of cold clouds are described and the distribution of areas favorable for cold clouds over the earth are discussed. Particular emphasis is placed on the possibilities for cold clouds associated with an extratropical cyclone. Specific examples of this type of storm are studied, including one that was viewed by the infrared sensors of TIROS II. A model is formulated showing an area favorable for cold clouds in an occluding extratropical cyclone.

1. Meteorology
2. Cold Clouds
3. Satellite Infrared Horizon Sensors

I. Alder, J. E.

UNCLASSIFIED

UNCLASSIFIED

AF Cambridge Research Laboratories, Bedford, Mass. Meteorological Development Laboratory
A METEOROLOGICAL STUDY OF COLD CLOUDS AS RELATED TO SATELLITE INFRARED HORIZON SENSORS, by J. E. Alder, February 1963. 64 pp.
AFCRL-63-413 Unclassified report

This report discusses meteorological aspects of cold clouds that affect infrared horizon sensors of satellites. Conditions favorable for the occurrence of cold clouds are described and the distribution of areas favorable for cold clouds over the earth are discussed. Particular emphasis is placed on the possibilities for cold clouds associated with an extratropical cyclone. Specific examples of this type of storm are studied, including one that was viewed by the infrared sensors of TIROS II. A model is formulated showing an area favorable for cold clouds in an occluding extratropical cyclone.

1. Meteorology
2. Cold Clouds
3. Satellite Infrared Horizon Sensors

I. Alder, J. E.

UNCLASSIFIED

UNCLASSIFIED

AF Cambridge Research Laboratories, Bedford, Mass. Meteorological Development Laboratory
A METEOROLOGICAL STUDY OF COLD CLOUDS AS RELATED TO SATELLITE INFRARED HORIZON SENSORS, by J. E. Alder, February 1963. 64 pp.
AFCRL-63-413 Unclassified report

This report discusses meteorological aspects of cold clouds that affect infrared horizon sensors of satellites. Conditions favorable for the occurrence of cold clouds are described and the distribution of areas favorable for cold clouds over the earth are discussed. Particular emphasis is placed on the possibilities for cold clouds associated with an extratropical cyclone. Specific examples of this type of storm are studied, including one that was viewed by the infrared sensors of TIROS II. A model is formulated showing an area favorable for cold clouds in an occluding extratropical cyclone.

1. Meteorology
2. Cold Clouds
3. Satellite Infrared Horizon Sensors

I. Alder, J. E.

UNCLASSIFIED

STANFORD
RESEARCH
INSTITUTE

MENLO PARK
CALIFORNIA

Regional Offices and Laboratories

Southern California Laboratories
820 Mission Street
South Pasadena, California

Washington Office
808 17th Street, N.W.
Washington 6, D.C.

New York Office
270 Park Avenue, Room 1770
New York 17, New York

Detroit Office
1025 East Maple Road
Birmingham, Michigan

European Office
Pelikanstrasse 37
Zurich 1, Switzerland

Japan Office
911 Iino Building
22, 2-chome, Uchisaiwai-cho, Chiyoda-ku
Tokyo, Japan

Representatives

Honolulu, Hawaii
1125 Ala Moana Blvd.
Honolulu, Hawaii

London, England
19, Upper Brook Street
London, W. 1, England

Milan, Italy
Via Macedonio Melloni, 49
Milano, Italy

Toronto, Ontario, Canada
Room 710, 67 Yonge St.
Toronto, Ontario, Canada