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Technical Report

QUANTITATIVE INTERPRETATION OF LOW-LEVEL CUMULIFORM CLOUD PATTERNS AS SEEN ON METEOROLOGICAL SATELLITE VIDEOGRAPHS

John A. Leese

E. S. Epstein
Project Director

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ABSTRACT

Cloud pictures from satellites present vast amounts of qualitative information about the physical processes taking place in the atmosphere. Utilization of the data in meteorological analysis requires a transformation from the cloud patterns to quantitative values which describe the physical processes. The purpose of this study is to devise suitable methods for making the conversion, based on the relationships found to exist between the parameters used to describe the cloud patterns and other meteorological variables.

The study is confined to the analysis of the low-level cumuliform cloud patterns which occur over the oceans. Observations were taken over the Northeast Pacific Ocean, between the west coast of North America and longitude 180 degrees and included the latitudinal zone from 20 to 50 degrees north. They were obtained over a three-week period in August and September by TIROS III in 1961 and TIROS V in 1962.

Confidence in the location of the satellite observations together with consideration of the quality of the other meteorological data constrained the minimum area of a cloud observation to that enclosed by 2 degrees latitude and longitude. The cloud patterns in the area were categorized by the amount of coverage, size of the cumuliform cells, and the size of the cloud bands if present. The location and time of the observation together with the meteorological data other than the clouds were used to form 23 synoptic parameters.

The synoptic parameters which were statistically related to the cloud variables were determined by the technique of multiple-discriminant analysis. Cloud amount was most closely related to the location of the observation with reference to the center of the anticyclone. Frequency distributions showed that the observations of cloud amount have a much greater variation from quadrant to quadrant within one sample period than is shown within one quadrant from one year to the next. Meteorological variables which showed a significant relationship with the cloud amount were: (1) latent heat transfer between the ocean surface and the atmosphere; (2) surface geostrophic wind speed; (3) difference between the geostrophic wind speeds at the 850-mb level and the surface; and (4) the air-dewpoint temperature difference at the surface.

The structure of the wind field between the 850-mb level and the surface was found to be the factor most related to the size of the

cumulus cells. The meteorological parameters, used to describe the wind field, which showed a significant relationship to the cell size were: (1) absolute vorticity on the 1000-mb surface; (2) surface geostrophic wind speed; (3) scalar difference in the wind velocities at 850-mb and the surface; and (4) the magnitude of the vector difference in the wind velocities at the same two levels. The longitude of the observing point also proved to be a significant parameter. The frequency distributions for the observations of cell size were quite different from one year to the next. The difference may be due to changes in the intensity of the anticyclone or to changes in the satellite attitudes from which the pictures were taken during the second year.

The observations of cloud bands for the two time periods were combined into one set due to the limited number in which banding was present. Discrimination among groups of band size was predominately between those without banding and the group wherein the spacing was classed as small. Above normal stability between the surface and the 850-mb level, most likely due to a subsidence inversion, was associated with the small-size bands. A combination of the surface wind speed with the temperature differences was also found to be important in discriminating among groups of cloud bands. The exact form of this combination could not be determined with a high degree of confidence.

A test was made to determine the capabilities for specifying the value of the meteorological variable, using the values of the cloud parameters and climatology. The cloud variables contributed only a small portion to the total "explained" variance. An analysis of the useful information contained in the parameters describing the cloud patterns showed that the cloud amount contributed most. The description of the cumulus cell size and banding added very little to the determination of the values for the other meteorological variables.

Suggestions for more sophisticated description procedures include increasing the number of groups for cloud amount, providing information about the cloud pattern on different size scales and using a coordinate system for describing the location of the observations in the anticyclone.

1. INTRODUCTION

1.1 AIM OF THE STUDY

The meteorological satellite has proven itself as a prodigious observational tool. The utility of the data obtained from this vehicle has been relatively low, due in large part to the meteorologist's lack of ability to interpret the information in terms of quantitative values for the more conventional meteorological parameters. Utilization of satellite meteorological data for research work has tended to be along the lines of case studies. Operationally, the meteorological satellite has proven to have its primary value as a reconnaissance vehicle in locating and tracking severe storms in the nature of hurricanes and typhoons. These two uses, important as they may be, involve only a minute portion of the available data. This study is intended as a step toward enhancing the utility of satellite cloud pictures by developing methods to analyze them in terms of quantitative meteorological parameters.

One of the simplest cloud patterns to interpret in terms of general synoptic conditions is that of convective clouds over oceanic regions. The capability does not extend to an explanation for the differences seen in these cloud patterns. Indeed, the nature of convective transfer processes in the atmosphere and the interaction of the oceans and the atmosphere are subjects in which meteorologists freely admit to a lack of knowledge. This study is concerned with using statistical methods in order to determine the synoptic-scale parameters which are significant in cellular convection. The descriptions of the cloud patterns are then used to determine the capabilities of obtaining quantitative information for the meteorological parameters from the satellite pictures.

The nature of the study is that of synoptic and inductive rather than deductive. Statistical relationships between the parameters used to describe the cloud patterns and those describing other meteorological conditions are sought. The relationships are then examined and interpreted in terms of physical processes.

1.2 THE APPROACH TO THE PROBLEM

Quantitative interpretation of the cloud patterns involves two interrelated problems which may be classified as physical and operational. The physical problem is concerned with the nature of convective transfer processes in the atmosphere and the interactions of the ocean and the atmosphere; the operational problem is one of data analysis and interpretation.

Multiple-discriminant analysis techniques are used to determine the meteorological parameters which make a significant contribution toward determining the pattern of the low-level cumuliform clouds. The contribution is significant in a statistical and not necessarily in a physical sense. The results are then used in an effort to gain quantitative information from the cloud patterns. Multiple-linear regression techniques form the basis for the statistical analysis in this part of the study.

Low-level cumuliform clouds appear quite regularly as an exclusive pattern in association with anticyclones, especially over the oceans. The Eastern North Pacific is dominated by a relatively stationary synoptic pattern of this type during the summer months. The mean sea-level pressure field for the month of August is shown in Fig. 1. Shipping lanes across this region between the west coast of North America and Asia as well as between California and Hawaii result in the availability of a relatively large number of surface meteorological observations. Satellite observations over this region were available for the period from August 15 to September 5 during the years 1961 and 1962. Observations over the Eastern North Pacific Ocean between 20 N and 50 N latitude and east of 180° longitude for the two time periods given above constitute the data sample for this study.

1.3 DESCRIPTION OF CUMULIFORM CLOUD PATTERNS

The meteorological satellite seemingly presented information about a new scale of atmospheric convection occurring in patterns with horizontal dimensions in the range of 10-100 mi. Figure 2 shows an example of this type of cloud pattern as seen on two different scales from satellites. The picture in the lower left is a reproduction of a photograph taken by the wide-angle lens on TIROS I. The limiting resolution in the picture is in the range of 3-5 mi. An enlarged view of the central portion of this picture, taken by the narrow-angle lens, is shown in the upper right. The limiting resolution for the enlarged portion is approximately 0.5 mi.

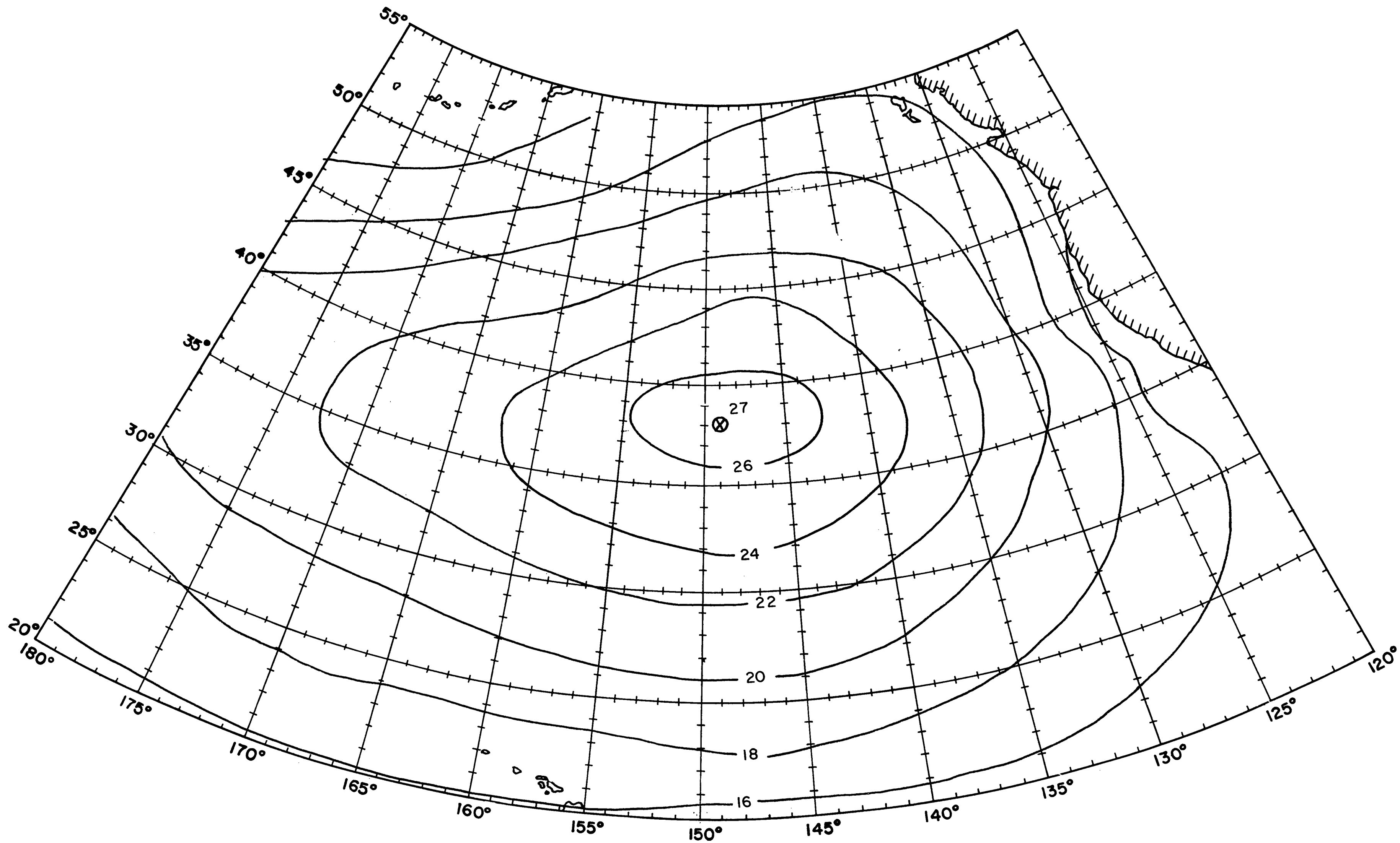

Fig. 1. Mean sea-level pressure (mb) for the month of August.
(U. S. Navy, 1956)

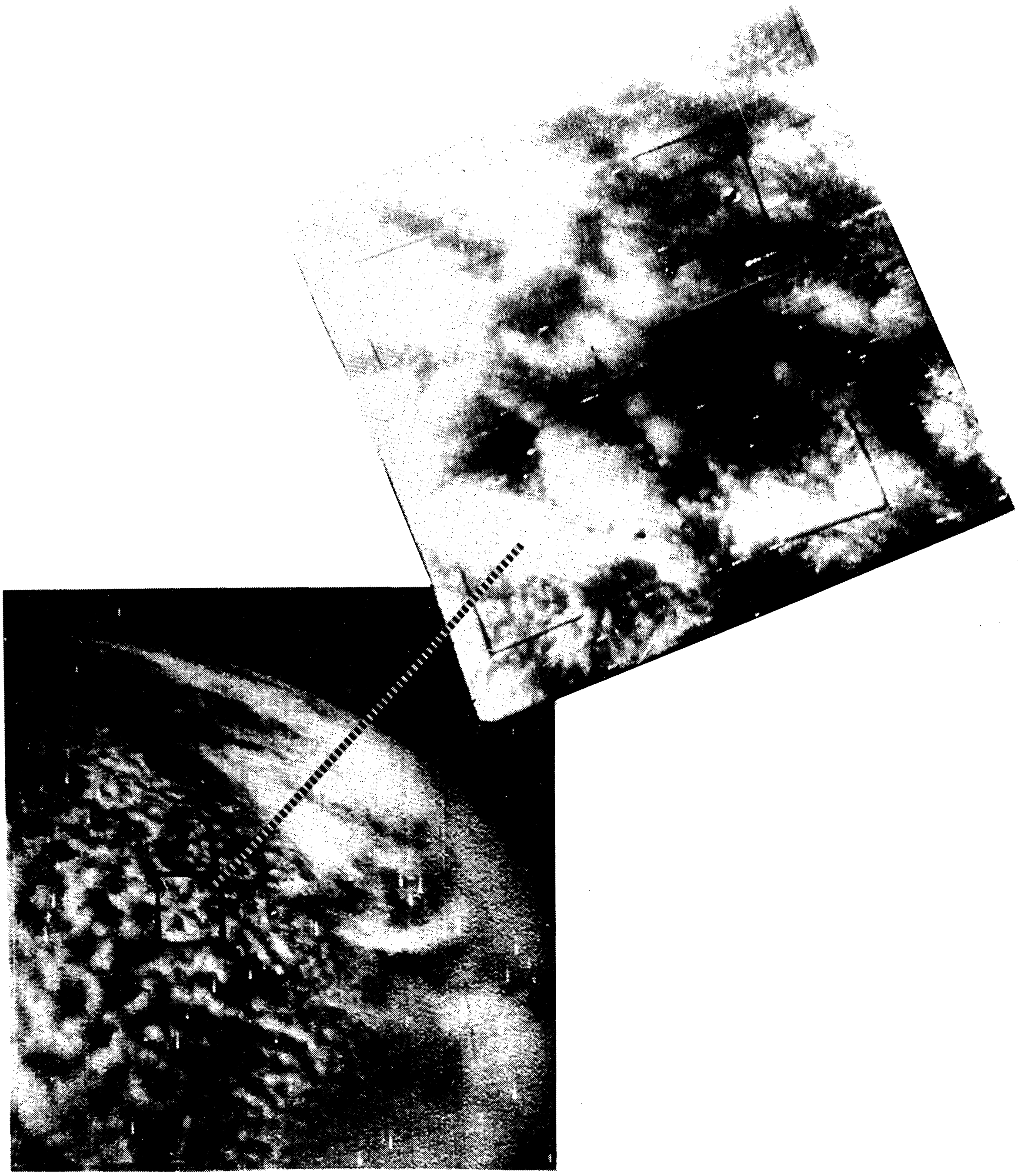

Fig. 2. Example of cumuliform cloud patterns as seen on two different scales from satellites. Narrow angle picture in the upper right corresponding to the area outline on the wide angle picture. (Inverted image of Fig. 13 in Krueger and Fritz, 1961.)

The widespread prevalence over the oceans of the type of clouds shown in Fig. 2 was not established until the advent of the meteorological satellite. A comparison of the detailed descriptions of this cloud pattern as seen from satellites (Krueger and Fritz, 1961; Conover, 1962, 1963) with descriptions of the cumuliform clouds usually seen in the tropics (Malkus, 1952, 1957, 1958; Riehl, 1954; Palmer, et al., 1955) reveals that these patterns are what the latter school commonly refers to as "cloud groups" or "bunches." Examples of these "cloud groups," as seen from aircraft altitudes, are shown in Figs. 3 and 4. Fig. 3 is a photograph of tropical cloud patterns taken from an altitude of approximately 30,000 ft near Jamaica. The agglomerates or groups of clouds separated by regions with few clouds are clearly distinguishable in this picture. The altitude at which the photograph for Fig. 4 was taken was not specified. It is most likely in the vicinity of 10,000 ft. This photograph shows some of the detailed cloud structure which can be found within the "cloud groups."

Malkus (1957) states, "Oceanic trade cumulus commonly appear in irregular groups about 10-50 km across, separated by somewhat wider clear spaces." Malkus further states (1958), "A cloudy area is composed of a small fraction of actively buoyant, rapidly rising updrafts, a comparable small fraction of strongly sinking, negatively buoyant downdrafts, and a great predominance area-wise of decaying cloud matter and weakly subsiding, slightly negatively buoyant air." Table I presents values of various parameters within a cloudy area which are representative values in un-

Fig. 3. "Groups" of cumulus clouds as seen from an altitude of approximately 30,000 ft. Taken over the ocean near Jamaica. (Photograph courtesy of Dr. A. L. Cole.)

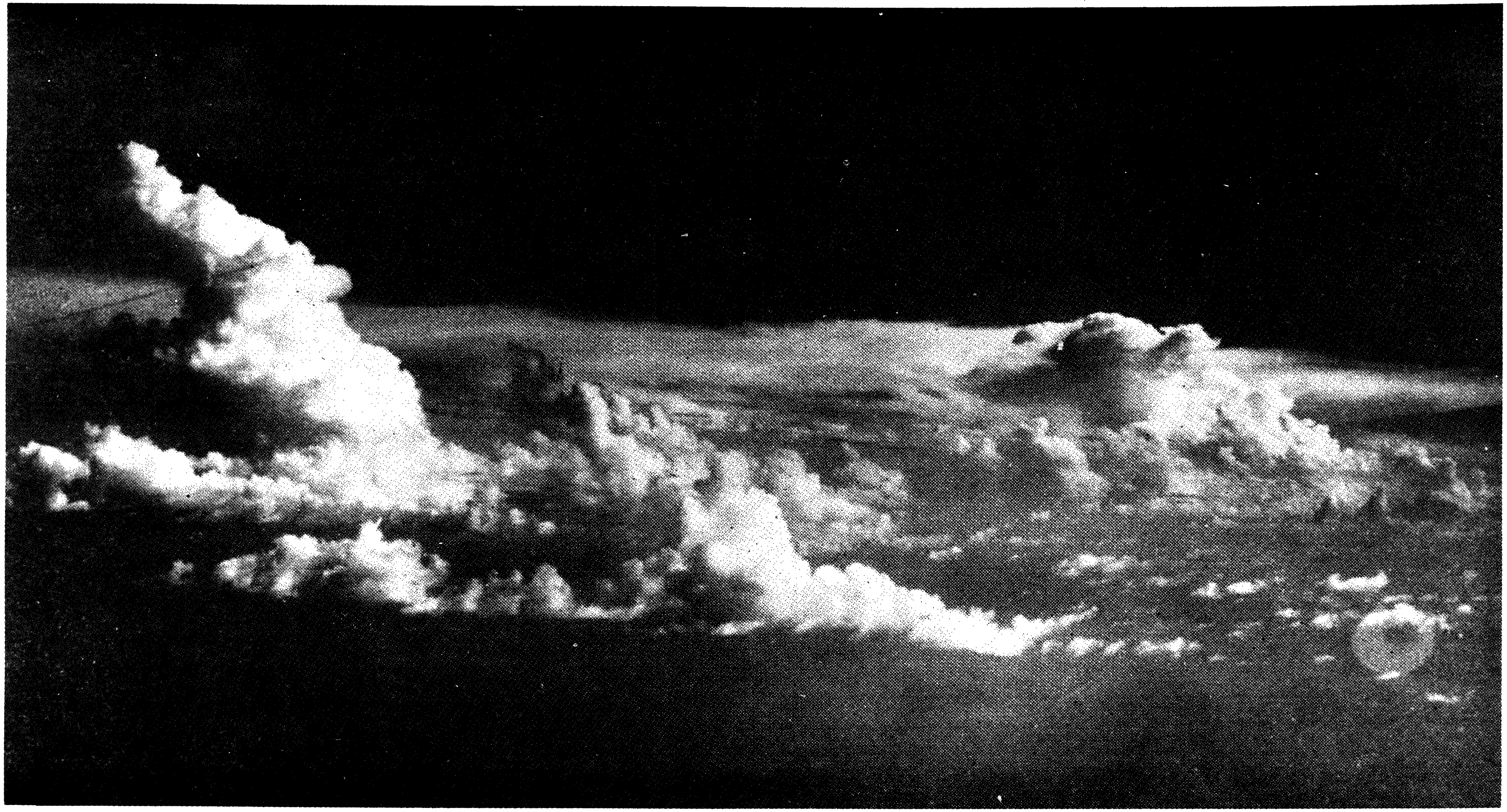

Fig. 4. Trade cumulus cloud group over the ocean near Puerto Rico, showing small cloudlets, larger towers with pronounced backslant (wind blows from left) and thin stratus sheet formed by cumulus speading below inversion base (Malkus, 1958).

disturbed regions of the trades, i.e., outside the vicinity of tropical disturbances. Malkus concludes that in such areas the cumulus and cumulus groups are thermally direct motion systems with the energy supplied by the release of latent heat.

TABLE I

DISTRIBUTION OF DRAFTS, VIRTUAL TEMPERATURES, AND MIXING RATIO ANOMALIES WITHIN A CLOUDY AREA (Malkus, 1958)

Category	Fraction of Cloudy Area	Draft, cm/sec	Mixing Ratio Anomaly (vs. clear), gm/kg	Virtual Temp. Anomaly (vs. clear), °C
Active updraft	1/20	+330	+2.3	+2.0
Active downdraft	1/20	-150	+2.1	-1.0
Inactive cloud matter	4/10	-5	+1.7	-0.1
Clear spaces between clouds	5/10	-4	+1.3	-0.3
Space average		+5	+1.5	-0.14

Riehl (1954) gives the life span of individual cumulus, with a thickness of 5,000-7,000 ft at peak development, as 1/2 hr or more. Of this time, roughly 10-15 min makes up the growing stage with the decaying stage lasting 20 min and more. Such clouds rarely persist for more than a few minutes without changing their shape and structure. For clouds which develop to the cumulonimbus stage, the period of growth may last about 1/2 hr and whereas the average life of a cumulonimbus is 60-90 min, it may last many hours. This life cycle refers to individual clouds and not the "cloud groups." The only reference located on the life history of cloud groups states that they begin as a large number of small cloudlets, of which a considerable fraction may later attain the precipitation stage together, and that on one occasion they persisted in nearly the same locality for at least 3-4 hr (Malkus, 1957).

2. REVIEW OF RESEARCH ON CUMULIFORM CLOUDS

2.1 PRELIMINARY REMARKS

Efforts have been made in the past, and are continuing to be made, not only to predict the future sky conditions at some location, but also to specify these same conditions at an initial time using other meteorological parameters. A degree of success has been achieved in attempts to specify layer-type clouds which form a continuous cover over an extensive area (cf. Ball, 1962; Davis, 1962). However, the work along these lines with low-level convective clouds has not achieved the same degree of success. Using a multiple regression technique, Ball was able to select specifiers (parameters derived from radiosonde observations) for low-level clouds in layers which gave a 63.4% reduction of variance of the specificand. When the same technique was applied to convective clouds he was able to obtain only a 14.8% reduction of variance. Previous efforts to diagnose cloud amounts have relied upon surface cloud observations for their source of data. Herein lies the major reason for their lack of success in specifying convective clouds. Satellite observations have been able to substantiate conclusively the fact that individual surface observations are incapable of giving any valid information about the amount of convective cloud cover present over a large area.

Our present knowledge of convection is based in large part upon laboratory experiments using compressible as well as incompressible fluids. Convection peculiar to the atmosphere has been described in innumerable papers on the subject. Up to now, the aircraft and camera have been the principal tools for observational studies of visible convection. Quantitative solutions for problems of convection have been obtained for only the very simplest cases in which the governing equations have been linearized. Efforts to obtain solutions for the nonlinear cases by numerical methods are now in the early stages. The remainder of this chapter is devoted to a description of the methods used and results obtained by previous workers in the principal areas of studies on convection.

2.2 CLASSICAL THEORY

A series of papers by Bénard (1900a, 1900b, 1901) describing his observations of cellular convection in a liquid, when the lower surface was at a higher temperature than the upper, have provided the impetus for a number of theoretical explanations of this phenomenon under various conditions. The bases for these theories are:

(a) Euler's equation of motion;

(b) the equation of continuity; and

(c) the equation of thermal diffusion.

In their fully developed forms these constitute a set of nonlinear partial differential equations for which it is necessary to make certain simplifying assumptions in order to obtain a solution. A review of the various methods used to linearize the above set of equations has been given by Stommel (1947a).

Rayleigh (1916) was one of the first to examine how far the observations of Benard could be explained theoretically. He assumed that gravity was the only external force acting on the liquid, and that the influence of density changes may be disregarded except insofar as it modifies the operation of gravity. He attributes the first use of this latter approximation to Boussinesq and it is now commonly referred to as the "Boussinesq Approximation" (Huschke, 1959). The result of Rayleigh's work was primarily the determination of an expression for obtaining the degree of instability necessary to overcome the dissipative influences of viscosity and heat conduction in terms of a nondimensional parameter now known as the Rayleigh number:

$$Ra = \frac{\alpha \gamma g h^4}{\nu K} \qquad (1)$$

where

α the coefficient of thermal expansion;

h the characteristic depth of the fluid;

g the acceleration of gravity;

γ $= -\frac{\partial \Theta}{\partial z}$, where Θ is the temperature, is the lapse rate existing in the depth of the fluid;

ν the kinematic viscosity; and

K the coefficient of thermometric conductivity, i.e., the ratio of the thermal conductivity k of a substance to the product of its specific heat c and density ρ: $K = k/c\rho$.

Equation (1) is the critical parameter in the theory of thermal instability. If its value is below a certain critical value, conditions are stable and any incipient convection currents are damped out by the combined effects of viscosity and conduction. The value of the critical number depends on the physical conditions of the problem, i.e., on the nature of the boundary conditions.

Rayleigh treated only one special case, i.e., one in which the top and bottom boundaries are free and the cells rectangular. Jeffreys (1926) extended this to include various forms of the boundary at the top and bottom. He reduced the problem to the solution of a linear differential equation of the sixth order with constant coefficients and obtained approximate values of the criterion for the stability by a method of finite differences. In a later paper (1928) he obtained solutions by assuming a trigonometric series for the differential equation and then obtained forms for lower derivatives by integration.

Rayleigh's mathematical treatment proceeds primarily in terms of the vertical velocity, and that of Jeffreys primarily in terms of the temperature. Both assume that equations expressing the conditions of neutral stability are obtained when second-order terms are neglected and all time variations made zero. The assumed regime entails steady velocity and temperature at any one point and the velocity is everywhere small.

Further extensions of Rayleigh's work were done by Low (1929) using boundary conditions with one surface of free slip and one of no slip; Jeffreys (1928) investigated the instability of a compressible fluid as a result of heating from below. Early investigators assumed the cell shapes were rectangular. Pellew and Southwell (1940) showed that this assumption was not required for an analytic solution to the equations. They represented the influence of the cell shape on the motion by a single parameter. The problem was then reduced to that of relating the cell shape parameter to the Rayleigh number.

The importance of rotation in relation to atmospheric convection was first suggested by Jeffreys (1928) but does not seem to have been treated quantitatively in detail until some 25 years later (Chandrasekhar, 1953; Chandrasekhar and Elbert, 1955). The effect of the Coriolis force was shown to inhibit the onset of convection. The extent of this inhibition depends on the value of the nondimensional parameter known as the Taylor number:

$$T = f^2 h^4 / \nu^2$$

where

f = the Coriolis parameter;

h = the depth of the cell; and

ν = the kinematic viscosity.

It was further shown that the instability can arise either as convection and a stationary pattern of motions or as over-stability and an oscillatory pattern of motions. Nakagawa and Frenzen (1955) have also shown that there are two modes of motion which can be considered solutions to their perturbation equations (an eighth order partial differential equation in the vertical velocity). They refer to one of these as "ordinary convective instability" and to the other as an "over-stable oscillation." Of particular importance in the present case is the possibility of resonance and interference developing between these two modes. They give an example for a particular set of conditions where the patterns produced in this manner would have a diameter of about 8 km. Frenzen (1962) uses this particular phenomenon to explain the cumuliform cloud patterns as seen by TIROS and described by Krueger and Fritz (1961).

Ray and Scorer (1963) express the opinion that the classical theory, because of the physical conditions assumed, is now recognized as being less realistic in terms of the conditions which actually make convection patterns possible in the atmosphere. They list the following as the principal differences:

(1) In the classical theory and experiments the fluid has a viscosity which is either constant or a function of temperature only. In the atmosphere the Reynolds number is so high that molecular transfer processes are of no importance in the bulk of the fluid, and instead there are eddy transfer processes which serve to damp the motion and make it steady in the mean.

(2) In the classical case there is a heat flux out of the top of the layer equal to the flux into the base, whereas in the atmosphere there may be a progressive warming or a radiative heat loss from the air and no appreciable conduction or other form of heat transport through the top of the layer, except possibly from a cloud top, but that would not be uniformly distributed. Because the stat-

ically neutral state is one with a temperature gradient there can be a radiative flux upwards through the layer, to which nothing exactly corresponds in the classical case.

(3) The flow circulates indefinitely and is symmetrical about the plane at the middle height; in the atmosphere the upcurrents are usually cloudy in the upper part of the layer, and the clouds do not spread out to form a complete layer at the top, but are mixed and evaporated continuously. The air between the clouds is stably stratified and has a much smaller level of turbulence than the cloudy regions and the layer below the cloud base.

(4) The Rayleigh number, which is proportional to the degree of static instability, is presumed or arranged in the classical case to exceed only slightly the minimum value necessary for cellular convection to occur. In the atmosphere, there is no mechanism for preventing the Rayleigh number from greatly exceeding the critical value if it exceeds it at all, and it generally does so by many orders of magnitude when calculated on the basis of the molecular transfer coefficients, which are the rates at which the transfers actually take place divided by the gradients of the quantities transferred, are very variable in space. They are also a by-product of the motion so that the Rayleigh number computed in terms of them must necessarily always be the same if all the other conditions except the degree of static instability remain unchanged. The motion therefore remains similar when the unstable temperature gradient is

increased or decreased, and the regular pattern remains the same.

This regular pattern is not, however, unique; but it depends on a variety of conditions among which the following are important: cloudiness, fraction of layer depth occupied by clouds, fraction of heat flux through the base which passes through the top as sensible heat, and lapse rate above cloud base.

2.3 EXPERIMENTAL STUDIES

The manner of the onset of convection by thermal instability in a layer of fluid heated below (or cooled above) has been the subject of many experimental investigations. The observations described by Bénard in 1900 and 1901 are undoubtedly the most widely known as the earliest reports of these cellular phenomena, although observations of a similar nature were described much earlier. Thomson (1862) attributed the accumulation of seaweed, leaves, etc., into long lines on the water surface to the action of convection in the water.

Bénard worked with very thin layers of a liquid, only about 1 mm deep, standing on a leveled metallic plate which was maintained at a uniform temperature. With the upper surface free and subject to evaporative cooling, a vertical temperature gradient is set up.

Subsequent experiments by numerous authors have followed the general approach of repeating those of Bénard using different fluids, compressible as well as incompressible, under varying conditions and of describing the patterns produced. Several experimenters have used the method of analogy in trying to find naturally occurring cloud patterns similar to the various convective patterns produced in the laboratory.

Idrac (1920) was among the first to observe that if a convective layer, such as Bénard's, possessed a relative velocity of general flow, then a series of vortices are set up with horizontal axes parallel to the shear.

Mal (1930) repeated and extended the experiments of Bénard and Idrac with liquids. He found examples of occurrences of similar cloud patterns in the atmosphere and observed the conditions existing at the level at which they formed. Mal was probably the first to show by observations that, in general, whenever a cloud layer is broken into polygons, rectangles, or lines, the layer is vertically unstable; but whenever the sheet is unbroken and continuous, it is stable. He further concluded that such a convective layer gives rise to a polygonal pattern when the shear is zero, to a rectangular pattern when the shear is small, and to a formation of longitudinal lines when the shear is large.

Phillips and Walker (1932) were unsuccessful in producing such lines transverse to the flow of a heated liquid moving along a rectangular trough. When they used unstable air as the fluid they found that by suitable increase of velocity from zero, the patterns produced were polygons, transverse vortices, crossed vortices (longitudinal and transverse), and longitudinal vortices. Similar patterns were found by Chandra (1938), but the precise forms depended on the magnitudes of the rate of shear and of the temperature differences within the chamber. The combination of longitudinal and transverse rolls has also been discussed by Brunt (1937, 1939, 1951) and used as an explanation for a variety of cloud forms observed in the atmosphere.

Experiments involving very high Rayleigh numbers (W.V.R. Malkus, 1954) have shown various modes and scales of convection. For Rayleigh numbers between 1.7×10^3 and 10^6 there were six discrete transitions observed in the slope of the heat transport curve. Further analysis by Malkus and Veronis (1958) showed that the initial heat transport due to convection depends linearly on the Rayleigh number, while the heat transport at higher Rayleigh numbers departs only slightly from this linear dependence.

The two modes of convection which theoretical considerations predict in a rotating fluid heated from below (discussed in the previous section) were found to occur in laboratory experiments with rotating cylinders of water (Nakagawa and Frenzen, 1955).

It can readily be seen that the experimental results just described have contributed significantly to our current knowledge of convection in the atmosphere. A criticism of some of the efforts to transfer, without suitable modification, observed conditions in the laboratory to those of the atmosphere would appear to be in order. This seems to be especially true in the case of cloud lines or bands. The fact that these patterns can be produced in the laboratory by shearing motion appears to be the sole basis for the criticisms of the other mechanisms advanced for the formation of patterns in the atmosphere. Shearing motions have not been conclusively demonstrated to be the mechanism for the formation of cloud lines in the atmosphere.

2.4 ATMOSPHERIC CONVECTION

2.4.1 Physical Model

The process which first lifts moist air to saturation can be any one or a combination of the following (Malkus, 1952): organized thermal-convective circulations in originally unsaturated air; unorganized thermal-convective bubbles; occasional eddies in a well-mixed layer randomly reaching their condensation level; wave motions within a layer or at an interface; updrafts caused by flow over barriers; and convergence in the large-scale circulation patterns, sometimes due to fronts, seabreezes, or frictional differences and possibly due to other effects not yet recognized.

The literature on the physical process of convection in the atmosphere shows distinct phases in the development of knowledge. Early investigations were primarily concerned with the thermodynamical relationships, the criteria for static stability and instability, and the amount of energy available for the creation of convective currents. The parcel method which assumes that a parcel of air may ascend or descend without causing any motion in the environment was the subject of many investigations around 1930. (See Pettersson, 1939; Petterssen, et al., 1945). The slice method which considers the downward as well as the upward currents, to preserve mass continuity, was introduced by Bjerknes (1938) and extended by Petterssen (1939). A further modification of the slice method was provided by Cressman (1946) by making allowance for net convergence or divergence inside the area. This effect was used to explain the fact that in regions of upward mass transport in the tropics the amount of cloudiness is frequently very large, although the lapse rate is only slightly greater than the moist-adiabatic value. These effects on convective motions have also been discussed by Marshall (1960).

Detailed observations within cumulus clouds by the Wymann-Woodcock expedition in 1946 showed that the lapse rate and the vertical gradient of the concentration of liquid water were different from those predicted by these two theories. As a result of these observations, Stommel (1947b, 1951) presented the entrainment theory which says that the ascending current in clouds entrain air from the surroundings. Synoptic studies by Austin (1948) showed that the lateral mixing of drier air from the environment into the ascending air of a cumulus cloud reduces the cloud temperature and thereby reduces the degree of instability. Criticisms of this simple model have centered primarily on the assumption of an average entrainment rate (Malkus, 1952) and on neglecting the continuous mixing and evaporation of cloud into clear air (Ludlam and Scorer, 1953).

The bubble theory of penetrative convection by Scorer and Ludlam (1953) attempts to take account of the effects of mixing clear air into clouds and the evaporation of clouds. In this theory a rising bubble of warm air sheds its outer skin steadily into a disturbed wake until it becomes dissipated completely or spreads out below a stable layer. The wake is a region where the ascent of further bubbles is favored. The size of these bubbles is in the neighborhood of 2 km. Large cumulus could then be composed of a number of bubbles and their wakes, in which there is a vigorous mixing with the surroundings.

Numerous studies of cumulus clouds have taken place during the past 10 years as a result of the bubble theory of convection. The erosion mechanism in the bubble theory was studied by Malkus and Scorer (1955) with an attempt to describe the process in quantitative terms. Wexler and Wexler (1960) made computations of cloud temperatures relative to the environment after the passage of successive thermals (bubbles) which entrain air from above and from the sides. Their computations show that after about the fourth bubble there is little change in temperature or moisture. Continued entrainment of dry air from the surroundings limits the amount of warming in the cloud as a result of the release of latent heat. The liquid water content of the cloud was also limited by the continued entrainment. An enlarged cloud entraining saturated air could result in further warming and an increase in the liquid water content.

Using results of laboratory experiments together with observations in the atmosphere, Woodward (1960) concluded that convective elements rising in the sub-cloud layer assume two basic forms—the spherically shaped isolated thermal and the rotating column. The effects of wind shear on an isolated thermal were studied by Hall (1962). His primary interest was in attempting to calculate the coefficients of heat and momentum transfer, where transfer is due solely to the rise of thermals.

The diameter of isolated thermals, emerging from the summit or on the flanks of a cumulus cloud, was found to have a well-defined upper limit by Saunders (1961) in an observational study of cumulus over land. The limiting diameter of the thermal was a simple linear function of the vertical distance it had penetrated with a coefficient of proportionality of 0.40. The increase of diameter with height was found to be insensitive to variations of the stability and humidity of the cloud layer and to the presence or absence of precipitation.

Recent evidence that these earlier formulations of the bubble theory are inadequate is provided by Warner (1963). On the basis of soundings made in convective situations, he concluded that a satisfactory explanation of the observations is only possible if account is taken of turbulent interchange both into and out of the buoyant element. He further concluded that the model of a linearly expanding thermal is valid only for the case of cumulus towers protruding into a still environment.

2.4.2 Observational Studies in Clouds

Detailed measurements in and around cumulus clouds were not made until after World War II. Prior to this the interpretation of environmental conditions in the presence of different cloud forms was based primarily on surface observations coupled with upper-air measurements made by balloon- or kite-borne instruments. A comprehensive review of the literature on parameters obtainable in an indirect manner from visual observations of clouds, primarily low-level cumuliform ones, was given by Brooks (1941, 1951).

An extensive aircraft observational program by the group at the Woods Hole Oceanographic Institution starting around 1946 has been the predominant source of data for detailed studies of the low-level cumuliform clouds over the oceans, especially in the tropical regions. (See Malkus (1952) for a detailed review of early findings of this group.)

As pointed out previously, the life cycle of these cumulus clouds is of such a relatively short duration that it is very difficult to make detailed measurements within the cloud at many levels. This was accomplished for two carefully selected clouds over the Caribbean Sea (Malkus, 1954). Observations with aircraft showed that a medium sized trade cumulus usually contains from one to three areas of upward motion with mean ascension rates of from 1-7 m/sec. The horizontal diameter of these areas ranges from 200-1500 m. It was possible to trace a specific updraft from one level to the next, although on some occasions two smaller-diameter drafts near the cloud base appear to join at a higher level to form a single rising column.

Downdrafts were encountered both inside and outside the cloud with speeds of descent of the same magnitude as those ascending in some cases. The strongest downdraft encountered in these measurements of cumulus clouds was approximately 4 m/sec. Malkus (1955a) concluded that, based on measurements of temperature and humidity, the downdrafts must be mixing primarily with the updrafts. She further concluded that these downdrafts gain their negative buoyancy mainly from evaporation and that they go through a life cycle of formation, strengthening, and decay which is closely dependent upon that of the updrafts.

2.4.3 Synoptic and Environmental Conditions

The literature on the subject of cumuliform cloud patterns could quite easily lead one to the conclusion that the only place conducive to their formation is the tropics and specifically the region of the trades. This conclusion is easily recognized as erroneous by one who has only casually glanced at pictures from satellites taken at other latitudes over the oceans. The reason for the great preponderance of literature on the subject of cumulus clouds over the tropical ocean (Malkus, 1960) is the relatively simple and uniform conditions which exist over large regions. The relatively uniform manner in which heat energy is supplied to the air from the ocean surface, as well as the existence of a moist layer quite uniform in the horizontal and nearly always conditionally unstable contribute in large measure to the simplicity of this regime.

Early studies have tended to concentrate on the cloud itself to the neglect of the environmental and synoptic conditions; a stepwise progression outward from the individual cloud to include a larger region of the environment can be noted in the literature. Thus, it has only been during the past few years that investigators have looked seriously at the cloud distributions in relation to large-scale flow patterns.

The most pertinent study for present purposes is the analysis of two sets of observations taken over the ocean near Puerto Rico in the spring of 1946 and 1953 (Malkus, 1958). The 1946 period was described as an interval of strong circulation for the location and season, whereas 1953 was characterized by weak circulation for the location and season. The cumulus were both sparse and poorly developed in the 1953 period compared to that in 1946. One reason for the poor cumulus convection in 1953 was found to be that the top of the mixed layer was more than 200 m below the condensation level on "poor cloudy days," indicating that the initial formation of small oceanic cumulus is controlled largely by processes in the subcloud layer. The most significant difference in the layer below the clouds between the two periods was the vertical moisture distribution. In the 1946 period, the mixing ratio was nearly constant with height in this layer, whereas in 1953 the air was more moist at the surface and drier at the top. The inference was that during the latter period the water vapor was not being transferred upward through the subcloud layer and was instead accumulating near the surface and acting to inhibit further evaporation. The most favorable condition for the formation of cumulus was a flow pattern with a strong northerly component. Such a flow in the region of Puerto Rico would give the maximum instability from the air-water temperature differences. The turbulent conditions in the subcloud layer results in more nearly optimum conditions for evaporation from the ocean surface and upward vapor transport.

Organized convection leading to large cumulonimbus buildups and precipitation in the tropics has long been recognized as being associated with synoptic-scale disturbances ranging from the easterly wave to the hurricane (Civilian Staff, 1945; Riehl, 1945). The seasonal oscillation of the inter-tropical convergence zone is readily discernible in the annual rainfall patterns at the affected stations (Riehl, 1954). The fact that large cumulus clouds and precipitation are highly concentrated in disturbed regions over the oceans as a general condition is strongly suggested from the results of cloud photography over the tropical Pacific Ocean in 1957 by the group from Woods Hole Oceanographic Institute. (Cf. Malkus and Ronne, 1960; Malkus, et al., 1962).

It will be shown in the following section that the detailed synoptic conditions associated with the existence of cloud streets in the migratory anticyclones of mid-latitude (Kuettner, 1959) are very similar to the average conditions found in portions of the Northeast trade winds (Riehl, et al., 1951). Evidence that synoptic conditions in mid-latitudes conducive to the formation of low-level cumuliform cloud patterns over the ocean are similar to those found in more tropical regions was presented by Krueger and Fritz (1961). Their studies indicate that this particular cloud pattern occurs in a region which (1) has a layer of moist air about 5,000 feet deep, heated at the ocean surface resulting in an adiabatic lapse rate; (2) has superimposed over this another layer of greater stability which serves to inhibit the convection; and (3) has little variation in wind speed and direction above that portion of the convective layer influenced by surface friction.

The amount of stratocumulus cloud in anticyclones moving over the British Isles has been shown to be related to the temperature and pressure at the base of the anticyclonic inversion (Findlater, 1961). More or less periodic fluctuations were found in these two parameters and these were attributed to shallow but distinct cold and warm areas which circulate in the lower layers of anticyclones. Findlater asserts that, "these cold and warm areas originate from successive pulses of cold and warm air on the flanks of anticyclones, but retain their identity after the fronts separating them have decayed and been omitted from routine analyses." The plausibility of this explanation can be readily accepted but one must also admit that tracing warm and cold areas of this size back to their original source over the ocean is very difficult at best.

Fluctuations have also been noted in the height of the trade inversion, but these have been attributed to divergence. The logical question at this point is; are the fluctuations the result of divergence, or vice versa? The diurnal variation in the height of the inversion has been attributed to the effects of diabatic heating of the clouds below the inversion (Kraus, 1963). Cooling of the cloud tops by radiational loss would result in an increase in the height of the inversion and therefore an increase in cloud depth. The end result of this influence is a precipitation maximum during the night over the ocean, which is substantiated by observations!

A unique hypothesis for the formation of cloud groups is that they result from "warm spots" in the ocean (Malkus, 1958). Using an airborne radiation thermometer, she found sea surface temperature differences from about 0.1-0.3°C were common on days with active cumulus convection. The extent of these "hot spots" ranged from 4-20 km along the direction of the wind. "Cold spots" of similar extent were also found. The extent of these areas normal to the wind were not determined. Simultaneous cloud observations showed that they were always associated with warm spots, with the cloud groups generally displaced slightly downwind relative to warm spots. Warm spots, usually with much smaller amplitude in temperature anomaly, were found without any clouds, but oceanic cloud groups were not found in the absence of temperature anomalies.

Malkus suggests a mechanism of the "equivalent mountain" for the initiation of cumulus groups similar to that which has been suggested is set up over a heated island (Malkus and Stern, 1953; Stern and Malkus, 1953; Malkus, 1955b). This mechanism will be discussed in the following section in connection with the formation of cloud lines.

2.4.4 Cloud Organization

The tendency for clouds to form in organized patterns on the scale of tens of miles or less was brought into focus by experimenters seeking patterns in the atmosphere similar to those found in the laboratory (Mal, 1930; Phillips and Walker, 1932). These patterns have been given various names of which the three most common are lines, bands, and streets. The origin of the last term as a description of cloud patterns has been attributed to glider pilots by Brunt (1937), who states "Cumulus clouds in long rows are now so well known to have ascending currents beneath them, making the conditions there suitable for gliding, that such clouds are known to glider pilots as 'cloud streets'." Still another term used by glider pilots to describe this phenomenon is "wind thermals," a term which Kuettner (1959) says expresses "... their observation that a combination of thermal convection and strong winds is required to produce cloud streets."

Although much of the early information about cloud streets was supplied by the detailed accounts of glider pilots, the details of conditions at the surface under these patterns was first described in connection with observations of the soaring habits of birds (Woodcock, 1940, 1942). These observations were taken over the open ocean, and in particular, Woodcock noted the existing wind speed and air-water temperature difference under which the sea gulls change their soaring technique from circling to straight flight. Figure 5 gives his results. Conditions for linear soaring appear to be quite restrictive with a surface wind speed in the range of 7-13 m/sec and an ocean surface more than 4°C warmer than the air above it. Circle soaring conditions are also somewhat restrictive being for the wind velocity between 0.5 and 7 m/sec and a water temperature at least 2°C warmer than the air.

In observing smoke patterns over the ocean, Woodcock and Wyman (1947) found that the general conditions prevailing whenever bands occurred were moderate surface winds with the lower air mixed, the upper air stable, and no heavy cloud cover. A more comprehensive study of the wind conditions prevailing in the lower atmosphere when cloud lines are present is provided by Kuettner (1959) in a study covering a 12-month period in the area of Boston, Massachusetts. He found that when cloud

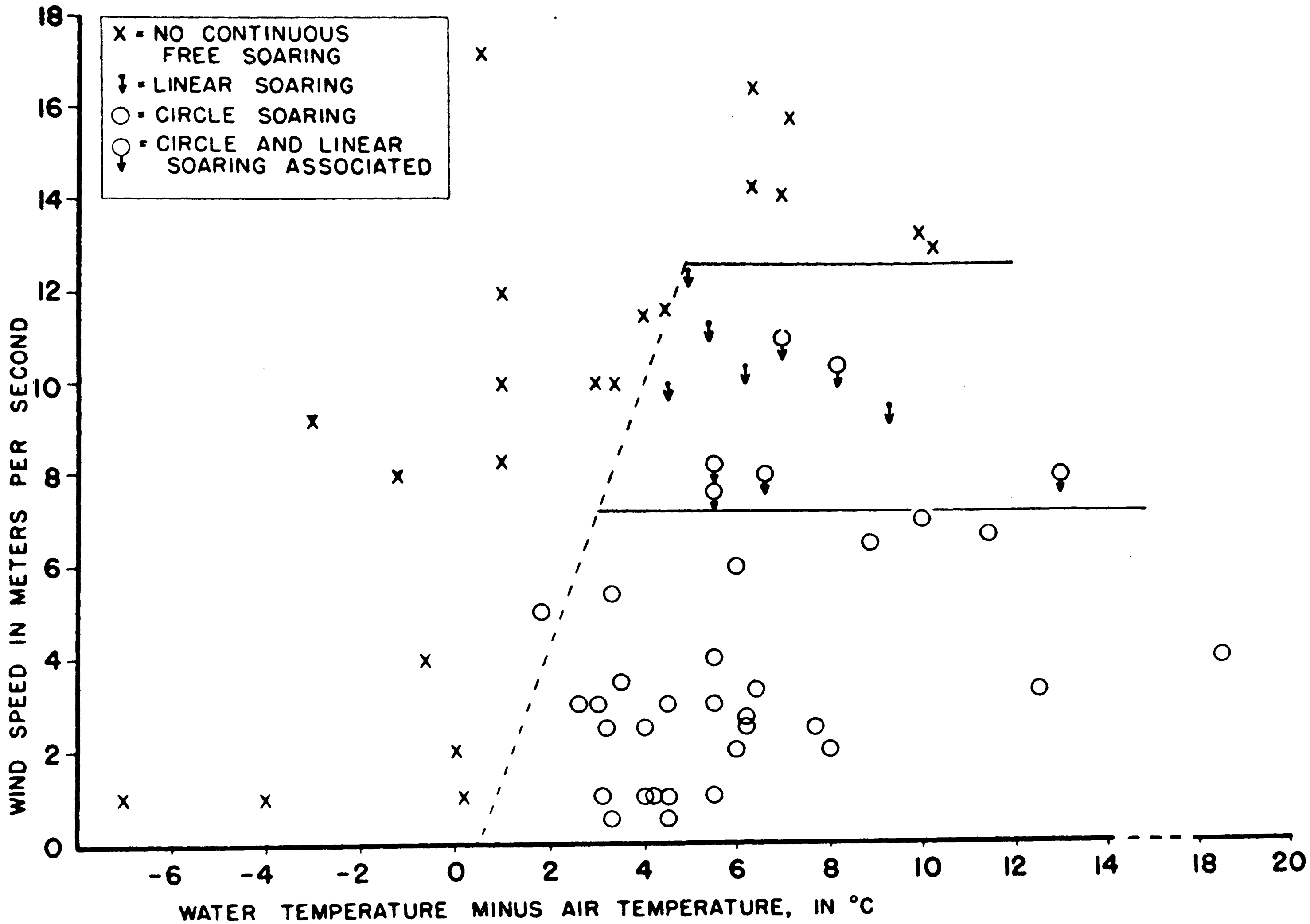

Fig. 5. Soaring habits of birds in relation to observed values of the wind speed and air-water temperature difference (Woodcock, 1940, 1942).

lines are present there is consistently a strong curvature of the wind profile and, in most cases, a definite wind maximum within the convective layer. There was very little variation of wind direction with height and a mean variation of the vertical wind shear with height throughout the convective layer of the order of 10^{-7} cm^{-1} sec^{-1}. He also noted what with rare exceptions the wind speed in the lower atmospheric layer was considerably higher than normal. In some of the cases, it was noted that a jet-like wind maximum occurred close to the ground. He attributes the occurrence of this wind maximum to the temperature pattern set up in the synoptic situation in which cloud streets occur. The synoptic pattern usually consisted of a cold high pressure area on the surface map in which the flow is from cold to warm with the cold center to the right and the warm center to the left. The temperature gradient in the vertical is such that the high pressure area has essentially disappeared by the 700 mb level, and except for the action of friction, the wind would be a maximum at the surface. He states that "the curved wind profile owes its existence to a frictional wind increase with height in its lower portion and to a thermal wind decrease in the upper portion, while the almost two-dimensional uniformity of the wind direction follows from the cold air advection of the low-level flow which gains heat during its progress."

Another factor in relation to the cloud streets studied by Kuettner is that they were nearly always topped by a stable layer or inversion at about 2 km above ground and quite close to the level of the upper wind minimum.

The importance of this analysis by Kuettner to the present study is that his complete description of the conditions existing in the lower layers of a migratory anticyclone when cloud streets are present shows many similarities to those which appear regularly in parts of the Pacific Anticyclone, especially in the region of the Northeast Trades. A more detailed discussion of the similarities is given in Section 4.

Extensive aircraft photographic studies were undertaken in 1957, both over Florida (Plank, 1960) and over the tropical Pacific Ocean. (Cf. Riehl, et al., 1959; Malkus and Ronne, 1960; Malkus, et al., 1961; and Malkus, et al., 1962.) Observations by the latter group revealed tropical clouds organized into what has been termed, "rows, regimes, and patterns." They deduced that the rows lined up in the direction of the predominant shear between the flow in the cumulus layer and its boundaries. As such, they distinguish between two modes of organization, a "parallel mode" and a "normal mode." (Later observations showed rows at varying angles to the wind other than normal, so the name of the latter was changed to "cross-wind mode.") Details of these two modes were given by Malkus, et al. (1962):

> The so-called "parallel mode" or cumuli in rows parallel to the low-level wind is often observed when a strong or dominant velocity shear exists between the cloud layer and the ocean below. The parallel mode is commonly exhibited by small trade cumuli when the easterly current shows negligible turning with height until way above their tops. The parallel mode is also commonly exhibited by high cumulonimbus towers in hurricanes and deep convective layers where the wind turns little or not at all through the main depth of the troposphere, commonly to anvil level.

> ... the cross wind mode appeared oriented along the shear between a rather uniform flow in the lower cumulus layer and another rather uniform flow in a deep layer above. In all situations studied there, the wind turning took place swiftly in a shallow stratum. No cases of row organization were found in which the wind turned continuously through a deep fraction of the cumulus layer; the latter is well-known to be a rather uncommon situation in the tropics.

The factors favorable to and inhibiting each of the modes of cloud organization based on the observations in the Pacific were summarized as follows (Malkus, et al., 1961):

A. Parallel mode

Factors favoring

1. Airflow over warmer ocean.
2. Strong low-level wind.
3. No wind turning with height.
4. Unstable cloud layer.
5. Synoptic-scale convergence.

Factors inhibiting

1. Airflow over cold ocean.
2. Weak low-level wind.
3. Rotation of wind at low-levels.
4. Inversion domination-stable and/or dry cloud layer.
5. Synoptic-scale divergence.
6. Very pronounced normal mode (?).

B. Normal (cross-wind) mode

Factors favoring

1. Cloud layer penetrating into upper shear or
2. Abnormally low shear superimposed on trade cumulus layer.

3. Disturbance (convergence).

4. Strong shear confined to narrow vertical layer.

Factor preventing
Uniform wind throughout troposphere.

Indications have been found that the proper conditions for rows existed prior to the formation of the clouds (Plank, 1960). Aerial photographs taken at the time that the first puffs of clouds were forming showed that these were already lined up in well defined rows.

The origin of cloud bands in the atmosphere has been attributed to a method analogous to that which is important in the formation of these patterns in the laboratory. Kuettner (1961) added to the model used originally by Rayleigh (1916), a horizontal flow of which the speed but not the direction was allowed to vary with height in an arbitrary manner. He showed that for marginal stability the vertical shear was approximately 10^{-7} cm^{-1} sec^{-1} in agreement with the value previously observed when cloud lines are present (Kuettner, 1959).

Haurwitz (1947) suggested that internal gravity waves may produce cloud lines, as well as the cellular, polygonal patterns. His equation for wavelength yields values of the order of 1 km for reasonable values of wind and temperature gradients in the vertical. Abdullah (1947) argued that it was necessary to account for the interference which takes place between two or more trains of waves and this necessitates the use of the theory of group-velocity. Using the wind and temperature data of Haurwitz, he found the stationary wavelength for individual waves to be of the same order of magnitude as those given by Haurwitz. Another solution to his equation corresponded to the stationary wavelength of the group as a whole and this gave values 10-100 times greater than for individual waves.

Sherman (1952) considered the buoyancy effects associated with the release of latent heat together with the kinematics of a deformation field to be such that the cloud is extended along the axis of dilatation of the deformative field of velocity. Such a mechanism would necessarily be restrictive in application as a result of observations of such patterns in dry thermals by glider pilots (Ray and Scorer, 1963), and clouds already in lines when they first become visible (Plank, 1960).

Bleeker and Andre (1950) expressed the opinion that the orientation of the rolls is mainly governed by the horizontal temperature field at the earth's surface. This is often such that differential heating exists along certain lines; along the same lines, the frictional properties of the earth's surface often vary which also favors organized convection. One might surmise that these authors are not discussing general conditions for cloud bands but have in mind the cloud patterns associated with the sea breeze "front."

A mechanism which also depends in large measure on differential heating is that of the "equivalent mountain" mentioned in the previous section (Malkus and Stern, 1953; Stern and Malkus, 1953; Stern, 1954). In studying the convective motions produced by the flow of a stable air stream over a small flat island, it was found that the heat source obeys an eddy conduction equation and is established by turbulent eddying in the mixed ground layer. One of the components for the streamline displacement was found to obey the equation for air flow over a mountain ridge, and thus an "equivalent mountain" corresponding to the heated island could be specified analytically. This pseudo-obstruction in the flow field depends on the temperature distribution along the surface, the wind speed, the eddy conductivity in the ground layer and the undisturbed stability, and its amplitude is related to the maximum streamline displacement. It was further shown that waves to the lee of this obstruction could occur if the undisturbed wind or stability undergoes a change in the vertical. This phenomena was used to explain the occurrence of periodically-spaced rows of small cumuli extending downwind from small islands.

Cloud observations from rockets (Hubert and Berg, 1955; Conover and Sadler, 1960) served to point out the various scales on which the organization of low-level cumuliform clouds could occur, but it remained for the meteorological satellite to show not only the frequency with which this organization occurs, but also that the scale of the organization takes in the whole spectrum of "wavelengths." Some of the first descriptions of these patterns were given by Widger (1960). The more unusual patterns found have been described as follows: by Bowley, _et al_. (1962), a wake pattern in low clouds to the lee of small islands in the eastern Pacific; by Hubert and Krueger (1962), horizontal mesoscale eddy patterns produced by obstacles in the flow and persisting for large distances downstream; and by the Monthly Weather Review.*

Attempts to quantify the cloud patterns have met with limited success up to now. Conover (1962, 1963) has taken a first step toward interpreting the patterns as seen from satellites by classing them into groups according to appearance with further subgroups classed according to size. The seemingly infinite variety of these patterns points to the futility of such an approach except on a very general basis. A two-dimensional extension of the familiar power spectrum analysis was used by Leese and Epstein (1963) to identify and quantify the statistically preferred dimensions and orientations of the cloud patterns. This method suffers from the fact that data must possess a quantitative format and the spectra must then be computed—expensive and time-consuming operations.

Merritt (1963), on the basis of a very limited sample, indicates the specific shape of a given cloud pattern can be related to the wind speed at the surface. He uses a range in speed of 10-12 knots for each class of the cloud pattern.

2.4.5 Summary

The literature reveals that the conditions within an individual cumulus cloud are known in great detail. When the domain is expanded to include more than one cloud the extent of our knowledge decreases rapidly.

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*A convenient means for disseminating pictures of these patterns on a continuing basis is provided by the "Picture of the Month" series in the Monthly Weather Review starting in 1963.

On the synoptic scale the present state of knowledge does not extend much beyond the general conditions favorable to the formation of low-level cumuliform clouds over the oceans.

Criteria used in this study to describe the cloud patterns, i.e., cloud amount, cumulus cell size and band size have previously been related to the prevailing synoptic conditions in only a very limited manner. On the basis of these few independent studies it is possible to reach a tentative conclusion that changes in the cloud patterns are accompanied by significant changes in the surface conditions. The previous studies for the most part had some upper air information available. This type of information is quite limited in the present study. Upper air variables used in the statistical analysis must be determined in an indirect manner. The decision to use a specific upper air variable was made on the basis of previous work. A more detailed discussion of this aspect of the literature is given in Section 4.

3. CLOUD OBSERVATIONS

3.1 SATELLITE ATTITUDE AND CLOUD RESOLUTION

The TIROS satellites have definite limitations to the coverage they can provide over any given area of the earth. Some of the restrictions are imposed by (1) the space-orientation of the satellite; (2) the amount of light necessary for proper exposure; and (3) the location of the ground stations for communicating with the satellite. A more detailed discussion of the TIROS limitations has been given by Widger and Wood (1961).

The amount of coverage available over the Eastern North Pacific (Fig. 1) is primarily determined by the location of the data readout stations on the East and West coasts of the United States. The result is a more comprehensive reconnaissance available when the satellite takes pictures on a track from the southwest to the northeast across the region than on a northwest to southeast track. The above conditions allowed for extensive surveillance of the region by the TIROS III cameras during the period from August 15 to September 5, 1961. A similar condition prevailed in the same period of 1962 with TIROS V.

The space-orientation of the TIROS satellites results in a different value of the nadir* angle for each picture taken during an orbit. During a three week period the latitudinal location for the occurrence

*The nadir angle is defined as the angle between the optical axis of the camera and the local vertical for the satellite.

of any given value of the nadir angle also varies. A convenient method to summarize the location of occurrence, as well as the actual values, of the nadir angles is through use of a model of the TIROS orbit (Glaser, 1961).

In this model the satellite attitude is defined by two parameters; the minimum nadir angle, n_o, and the time of occurrence of this minimum, t_o. In the case of a circular orbit the nadir angle n can then be expressed as a function of n_o and ϕ; where ϕ is the difference in time between the occurrence of n and n_o. A nomogram showing the values of n as a function of ϕ and n_o for a TIROS satellite with an orbital period of 100 min is given in Fig. 6.

The orbital plane of TIROS III was inclined at an angle of approximately 48° to the equator while TIROS V had an angle of inclination of approximately 58°. The period of each was near enough to 100 min so Fig. 6 can be used. The portion of the subpoint tracks between the equator and the northern limit for both TIROS III and V are shown in Fig. 7. The time marks on each of these tracks refers to the time after the ascending node (point where the orbit crosses the equator on the northbound leg). The orbit of TIROS III was sufficiently close to circular so that a general orbit can be constructed. According to Goldshlak (1963) this was not the case for TIROS V. The ellipticity of this orbit was large enough to give subpoint location errors as large as 200 mi along the track if such a general orbit is used.

The values of n_o and t_o for the three week periods are shown in

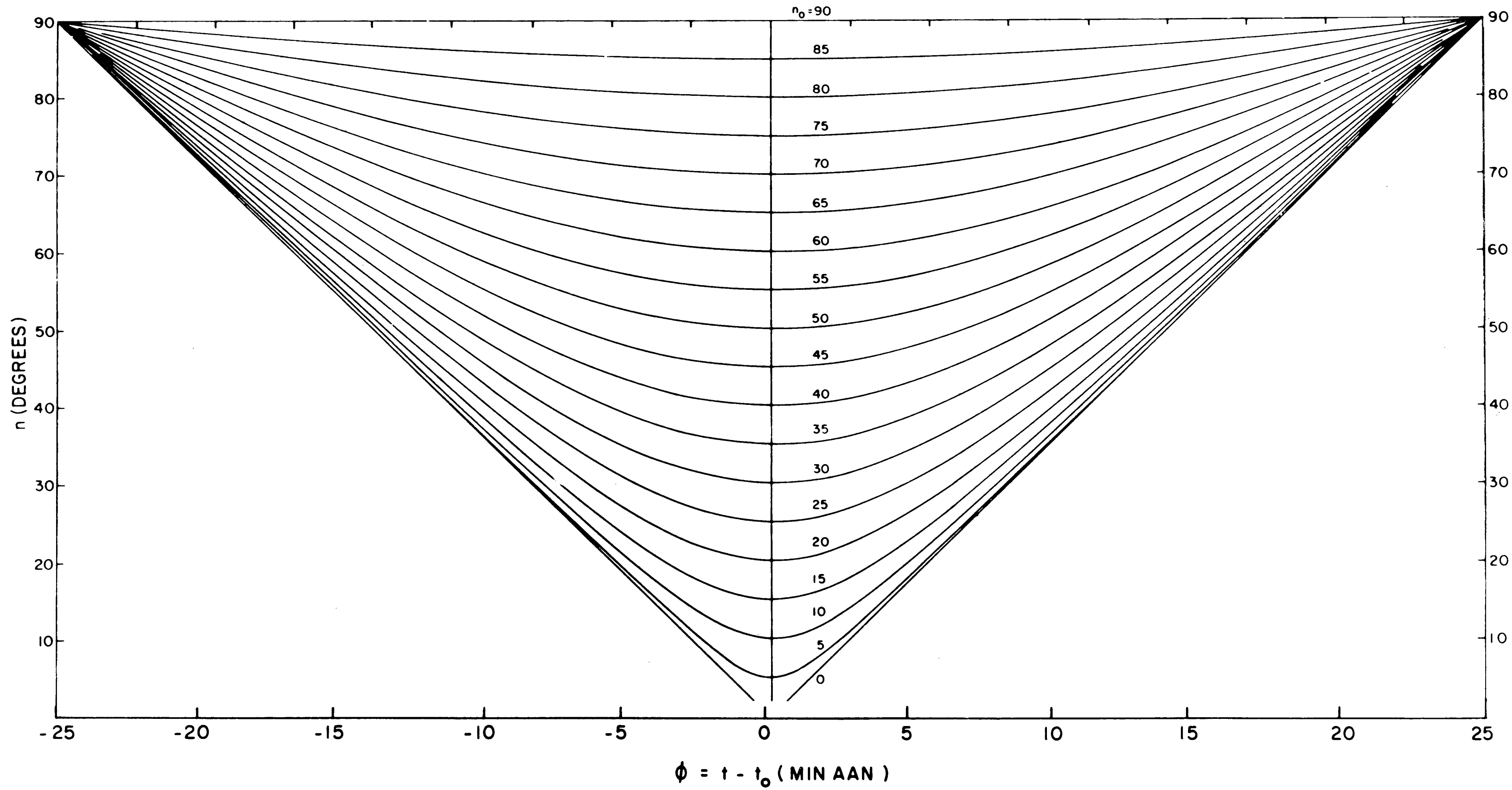

Fig. 6. $n(\phi, n_o)$ for a general orbit with a period of 100 min. (Modified figure presented by Glaser, 1961.)

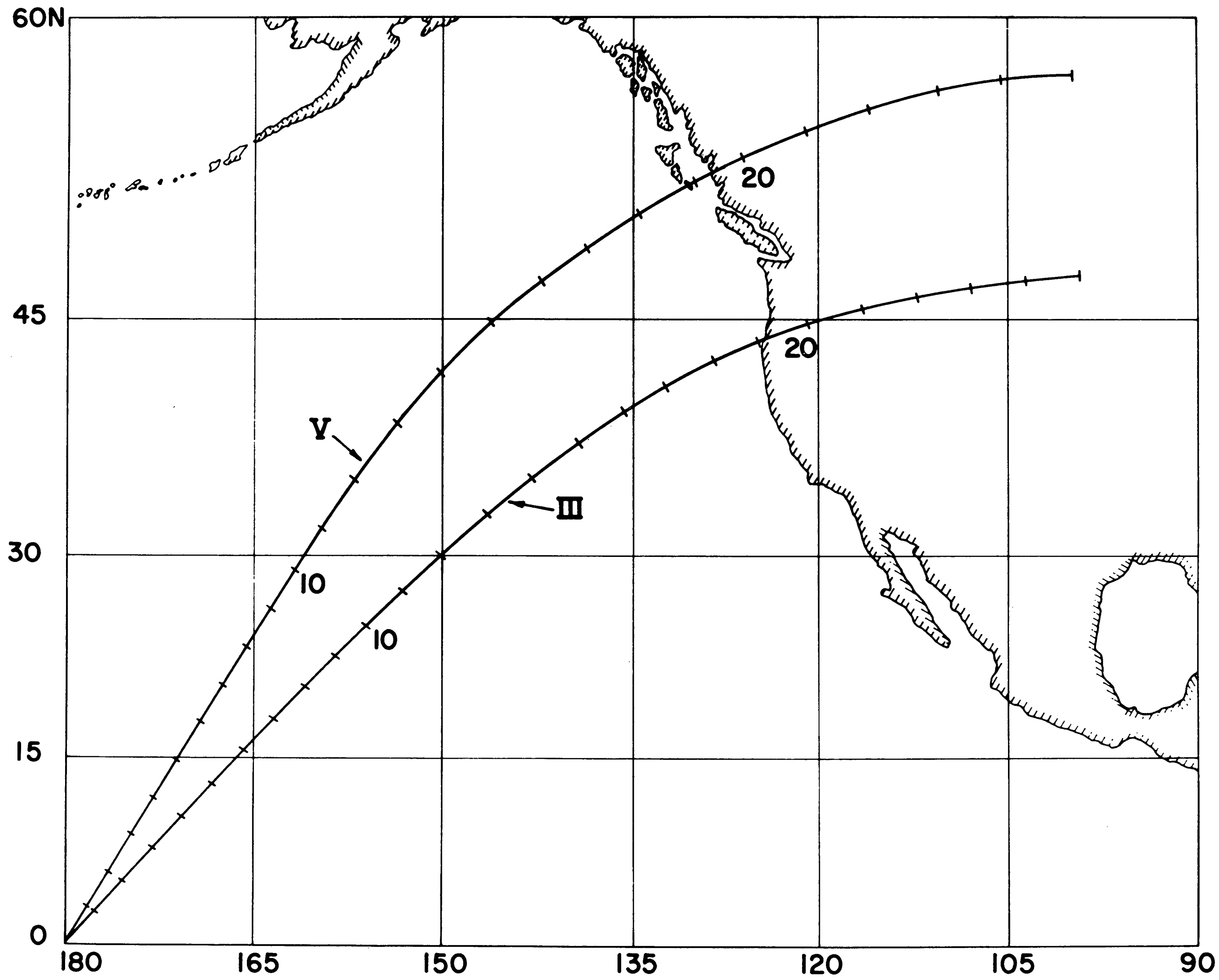

Fig. 7. Subpoint tracks between the equator and the northern limit with the ascending node at 180° for both TIROS III and V.

Fig. 8 for TIROS III and Fig. 9 for TIROS V. The source of the data for Fig. 8 was Goldshlak (1962), while Fig. 9 was constructed from data presented in Goldshlak (1963). Ordinate scales on each of the figures are t_o in minutes and n_o in degrees. Positive values of n_o indicate that the camera axis was pointed north of the track. The value of t_o refers to the time after the ascending node which can be converted to the approximate value of the latitude by referring to Fig. 7.

Figure 8 shows that, at the beginning of the period, the value of n_o was about -7° which occurred approximately 5 min (latitude 12S) before the ascending node. During the three week period the time of occurrence progressed beyond the northern limit of the orbit to about latitude 47N on the southbound leg, with a final value of n_o near +30°. TIROS V also started the period looking to the south of the orbital track with a value of n_o of approximately -18°. This occurred in the vicinity of 30N ($t_o \approx 10$). By the end of the period the value of n_o had changed to +20° and was still located on the northbound leg near 55N.

The nomogram (Fig. 6) can be used in conjunction with the general orbit (Fig. 7) and the attitude summaries (Figs. 8 and 9) to determine the approximate range of nadir angles which occurred between latitudes 20N and 50N on any given day during the two periods.

On any specific picture the perspective angle can vary from zero to approximately 65° (horizon angle for TIROS) if a horizon is present. The resolution is found to be quite sensitive to the value of this perspective angle. Gray (1964) gives the following values for the resolution:

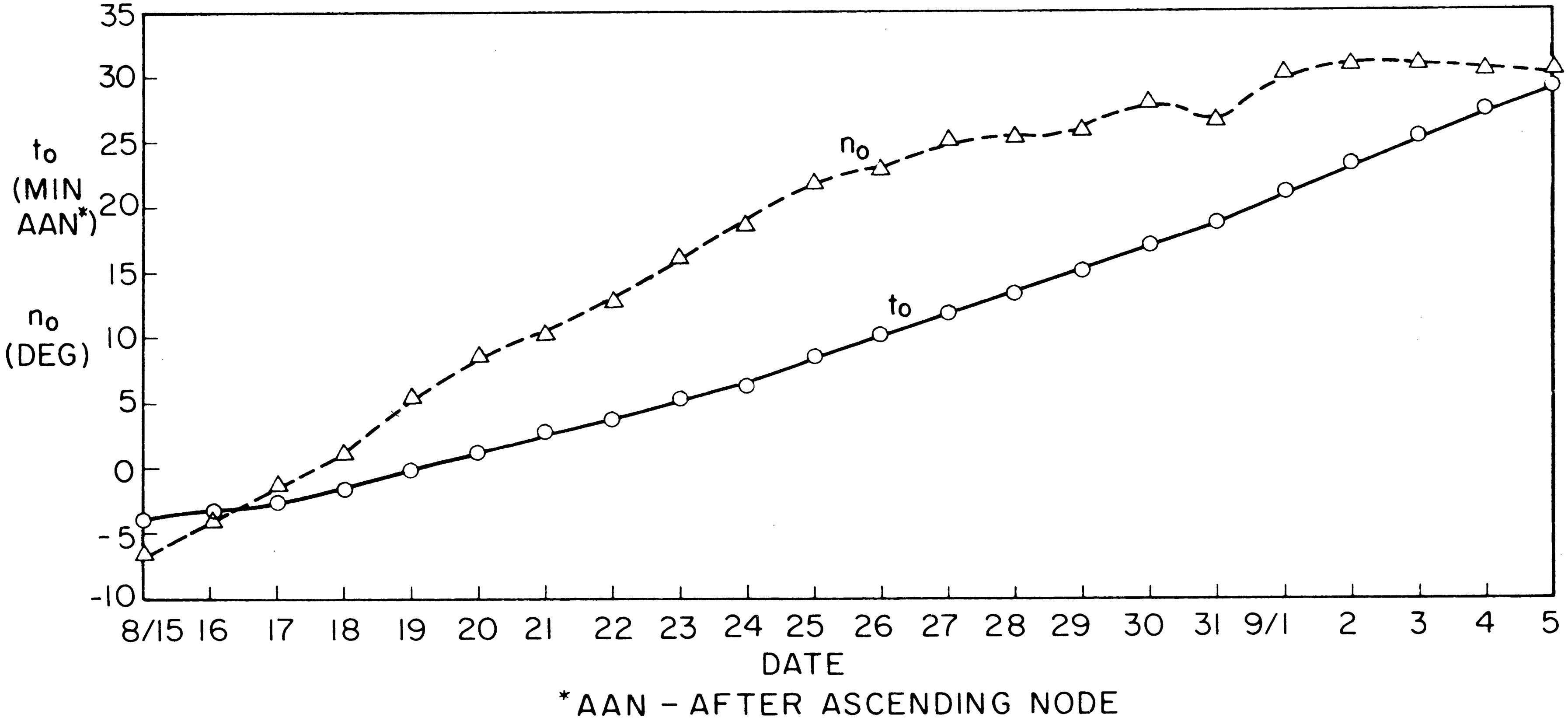

Fig. 8. Values of n_o and t_o for the period August 15, to September 5, 1961, for TIROS III.

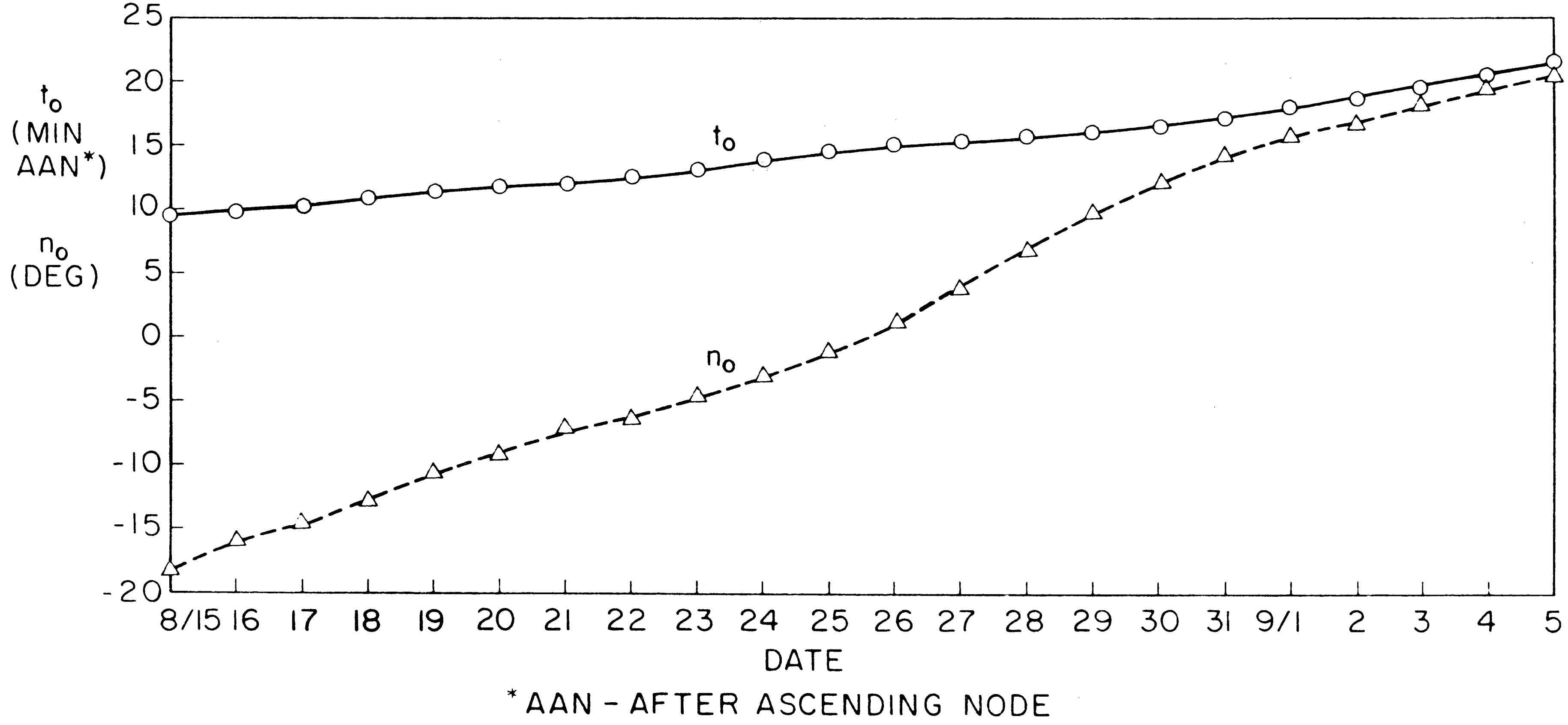

Fig. 9. Values of n_o and t_o for the period August 15, to September 5, 1961, for TIROS V.

2 mi when looking straight down, 4 mi at an angle of 45°, and 6 mi with a nadir angle of 55°.

3.2 LOCATION AND CLASSIFICATION

The satellite data were reanalyzed even though much of the information about the cloud patterns needed for this study was already available on nephanalyses from the National Weather Records Center in Asheville, North Carolina. These were made on an operational basis at the data readout stations shortly after the satellite data were received. The analyses were found to be quite an aid for getting a first approximation to the limits of coverage available as shown in the catalog of satellite data (U.S. Weather Bureau, 1962, 1964). However, they were found to be too coarse for the parameters needed in this study, especially in the location of the geographical boundaries between the different cloud groups. They also contained no information about the uniformity of the cloud distribution within a given area.

Latitude and longitude grids for many of the pictures were recomputed by the Meteorological Satellite Laboratory. Hubert (1962) points out that inconsistencies exist between the computed grids and the operational nephanalysis, and that the computed grids should be better in overall accuracy. This factor plus those described in the previous paragraph made it desirable to obtain the cloud observations from the original pictures superposed on the computed grids. It was assumed that the computed grids were accurate to within 2° latitude of the true location.

A cloud observation was defined to be an area on the TIROS cloud picture of at least 4° "square" comprised of a cloud pattern having uniform coverage and pattern arrangement. The location of the observation is the latitude and longitude at the center of the area. (Four degrees "square" is defined as the area included by two latitude circles separated in latitude by 2° and two longitude circles separated by 2° longitude. This yields an average area between 20° and 50° latitude of approximately 40,000 km^2, with a maximum deviation of about 20%. Deviations from equal area are neglected.) Each observation is composed of the amount of cloud cover, the size of the cumulus cells, the size of the bands if they are present. The amount of cloud cover falls in one of six groups composed of:

1. clear,
2. clear to scattered,
3. scattered,
4. scattered to broken,
5. broken, or
6. broken to overcast, and overcast.

Since a cloud observation is by definition an area having uniform coverage, these groups refer primarily to the actual amount of clouds present as opposed to a description of nonuniformity, as might be suggested by the nomenclature of groups 2, 4, and 6. Quantitatively, the six groups correspond to the following amounts of cloud cover in eighths:

Group	Octa
1	0
2	1,2
3	3,4
4	5
5	6
6	7,8

The cumulus cell size over the area is recorded as one of the following six groups:

1. none,
2. small,
3. medium,
4. large,
5. mixed, or
6. undetermined.

The cell size was determined by inspection. Individual cells less than 10 km were classified as small, between 10 and 20 km as medium, and greater than 20 km as large size. Any of these three groups could result from an unresolved agglomeration of individual cells, and especially in oceanic areas it is realistic to assume that a sizable portion of the observations in the group of large size are the result of this agglomeration. Even so, the scale of agglomeration is of interest. For clouds in lines or bands, the cell size was given as the width of the band. The group composed of mixed size are those observations in which size of the cells could be determined but did not fit any of the other three specific categories. No attempt was made to be more explicit by subdividing this category. The size was undetermined when the amount of cloud cover was overcast or breaks in the cloud cover were so few that determining a cell size was unrealistic. The category of none is primarily composed of observations of clear but also contains observations in which only a few clouds existed over the area, in which case it was felt that assigning a specific cell size to the whole area based on so few clouds would be unrealistic.

The question of bands in the cloud pattern was a simple yes or no based on whether or not bands were obvious over the area. If bands were present, the size was classified as small when the spacing was less than about 30-40 km and large for the remainder. This subjective method of determining the presence of bands in the cloud pattern undoubtedly missed cases in which banding was not obvious by sight and which would have been found by a more objective technique, such as two-dimensional spectral analysis. No attempt was made to classify the orientation of the bands.

Since this study is intended to be confined to dealing with the relatively simple case of one specific cloud pattern, i.e., low-level cumuliform, all the observations were subjected to close screening, especially for large amounts of cloud cover in close proximity to fronts, to further insure that this was the case.

3.3 GEOGRAPHICAL DISTRIBUTION

Observations were recorded for all passes of TIROS III and V which contained pictures over the region and were within the specified dates. For TIROS III these conditions occurred for the first time on August 18, 1961, and continued through the remainder of the period for a total of 72 passes containing pictures over the region. After screening the observations for proximity to fronts, a total of 879 observations remained. With TIROS V, in the 1962 period, there were 42 passes which contained pictures over the region from which 862 observations were obtained. Tables showing the distribution of the observations for each of the cloud variables, from both TIROS III and V, within subregions of 5° latitude and longitude are given in Appendix A.

A more natural breakdown of the distribution of the cloud observations is the frequency of occurrence of these various cloud patterns within quadrants of the Pacific Anticyclone. The lines of 35N latitude and 150W longitude (Fig. 1) serve as the interior boundaries of these quadrants. Such a distribution for the observations of cloud amount is given in Fig. 10. The geographical distribution of the observations within the four quadrants is proportionately very similar in the two years. The distributions of the observations of cloud amount are also very similar from one year to the next. The only important changes occur in the NW and NE quadrants which have a smaller percentage of observations in group 6 in 1962 than in 1961. In the NW quadrant, the de-

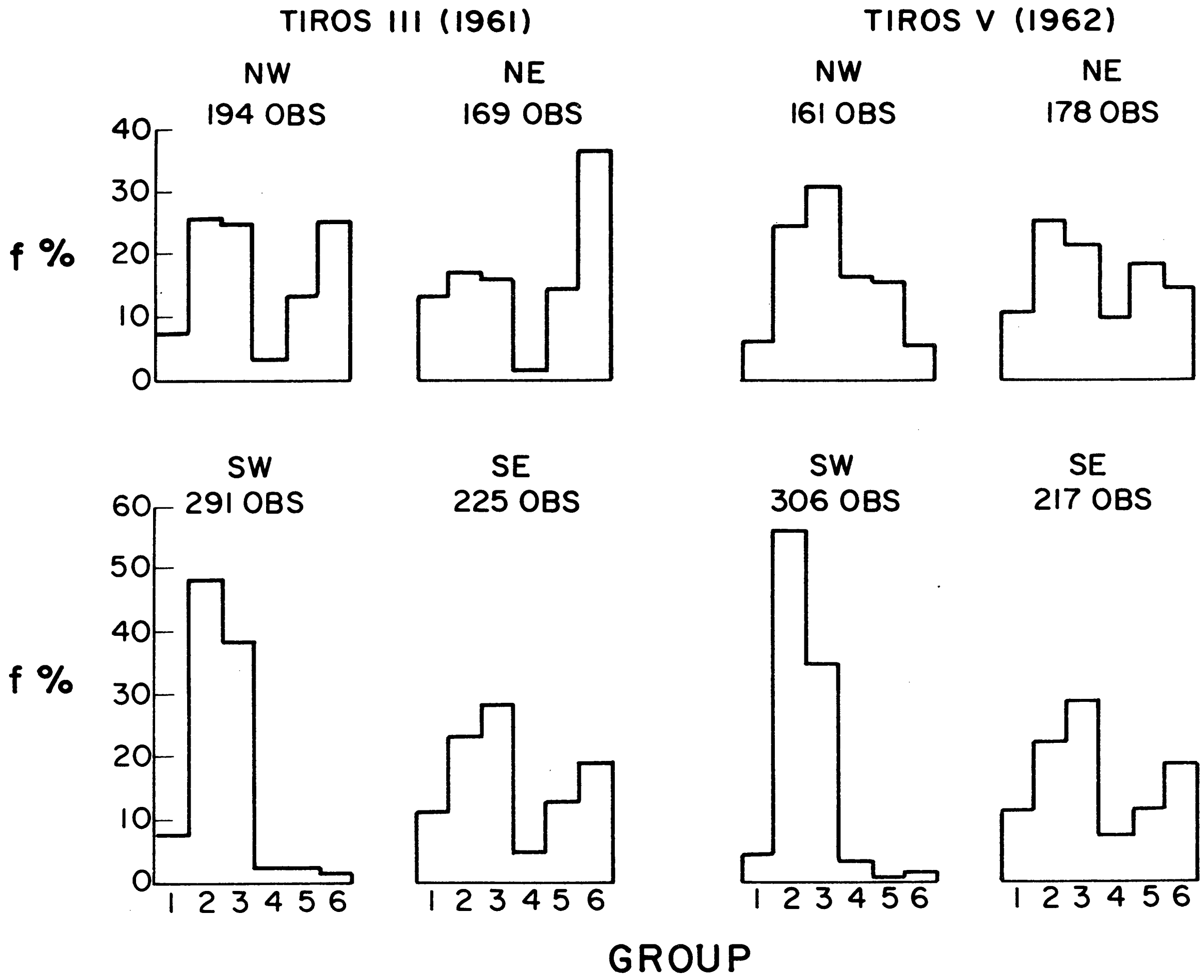

Fig. 10. Distribution of cloud amount observations by quadrants for the two time periods.

crease in group 6 was shifted to groups 3 and 4 which had a sizable increase in the percentage of total. On the other hand, the NE quadrant had a shift toward groups 2, 3, and 4. One of the most important features shown in Fig. 10 is that the observations of cloud amount show a much greater variation among the different quadrants within one time period than is shown by the same quadrant from one year to the next.

In a given year, the two northern quadrants have quite similar distributions of cloud amount. In 1961 these showed a strong tendency toward a bimodal distribution with the first mode between groups 2 and 3 and the second at group 6. This distribution was not as apparent in the NE quadrant in 1962 and the NW quadrant had a definite unimodal distribution in this time period with the mode between groups 2 and 3. The southeast quadrant shows a more frequent occurrence of smaller cloud amounts, especially in 1961, but maintains a shape in the overall distribution quite similar to the northeast quadrant. The frequency distribution of cloud amount in the southwest quadrant shows a very unique shape. Approximately 86% of all the observations in this quadrant during the 1961 period contained cloud amounts of clear to scattered or scattered, i.e., groups 2 and 3. In the 1962 period the proportion of all observations in these two groups was slightly greater than 90%. One reason for this distribution is discussed in the next section.

The distributions of the cumulus cell sizes of small, medium, large, and mixed in the four quadrants are shown in Fig. 11. These categories of cell size are almost exclusively associated with the cloud amount in

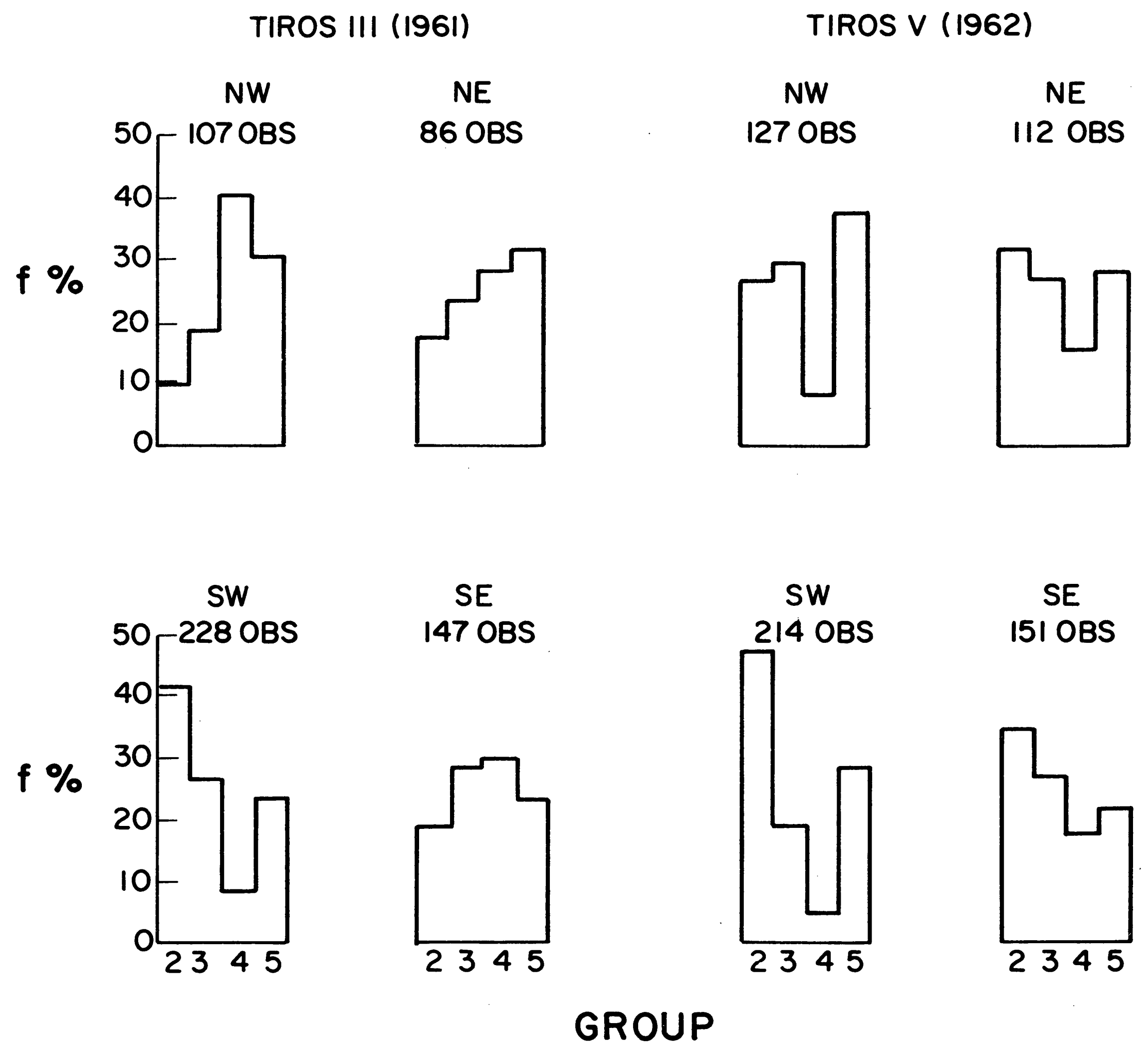

Fig. 11. Distribution of observations of cell size by quadrants for the two time periods.

groups 2-5. The most striking feature is the large decrease in the number of observations having a cell size classed in group 4 in the 1962 period from what was observed in 1961. The fact that a proportionate decrease appears in all the quadrants on the second year strongly suggests it is not all real. The author is of the opinion that a slight change in procedure for obtaining the cloud observations in the second year may have induced a bias in the determination of the cell size.

Gray (1964) suggests two other reasons for the differences in the distributions of cell size during the second year. The anticyclone on the average was more predominant over the entire region during the 1962 period than it was in 1961 (compare Figs. B-1 and B-2 in Appendix B). This resulted in a greater frequency of occurrence of organized patterns with small cell sizes during the 1962 period. The observations of band size (Table II) show a definite increase from one year to the next.

Another reason for the change could be due to the differences in attitude of the two satellites during the period of interest as well as the enhanced gray scale resolution from TIROS V. Figure 9 shows that the value of n_o for TIROS V was lower than that for TIROS III (Fig. 8) for most of the period. This indicates that the pictures from TIROS V were obtained at a lower nadir angle and therefore had a lower limit of resolution than did those from TIROS III. The gray scale on the pictures during the 1962 period was also of better quality than during 1961. The lower nadir angles and the enhanced gray scale increased the capability to resolve individual cells in the cloud patterns during the 1962 period.

The probable existence of bias in the TIROS V observations of cell size precludes any comparisons possible in the frequency distribution of this cloud variable between the two time periods. The TIROS III observations show the distribution of cell sizes on the absolute scale, i.e., that cells less than 10 km are classified as small, between 10 and 20 km as medium, and greater than 20 km as large size. The TIROS V observations show the distributions of cell size on a relative scale within the set, but cannot be assigned an absolute scale for the limits of cell size within the three groups of small, medium and large.

During the 1961 period the large and mixed cell sizes were predominant in the two northern quadrants. The northwest quadrant has almost 73% of the four sizes in these two categories while the northeast quadrant had approximately 60% of the observations in the two groups. On the other hand, the four size groups are about equally likely in the southeast quadrant. The southwest quadrant again, as in the distribution of observations of cloud amount, shows a very unique shape in the frequency distributions of cell size. Nearly 48% of the observations in these four categories are classified as small, whereas less than 8% are large size.

The frequency distributions of the observations in which banding was present are shown in Table II. The total number of cases in which banding was present in the 1962 period was 92 more than the number observed in the previous year. This increase was primarily in the occurrences of small bands, i.e., a spacing of less than about 30-40 km. The large increase in the number of occurrences of banding found in the northern half

TABLE II

DISTRIBUTION OF BAND SIZE OBSERVATIONS

Quadrant		TIROS III (1961)			TIROS V (1962)		
		2	3	Total	2	3	Total
NW	F*	10	14	24	38	21	59
	% (all obs)	5.2	7.2		23.6	13.0	
NE	F	9	8	17	40	18	58
	% (all obs)	4.7			22.5	10.1	
SW	F	39	14	53	22	12	34
	% (all obs)	13.4	4.8		7.2	3.9	
SE	F	20	32	52	55	32	87
	% (all obs)	8.9	14.2		25.3	14.8	
All	F	78	68	146	155	83	238
	% (all obs)	8.9	7.7		18.0	9.6	

2 - small 3 - large

*F = frequency.

of the region in 1962 accounts for a major portion of the total increase. In the 1961 period the tendency for clouds to occur in bands was quite a rare event in the northern half; being present in only about 11% of the observations. The following year banding was apparent in approximately 35% of the observations from this part of the region. The TIROS III observations showed that the greatest likelihood of banding was in the southeast quadrant. Nearly one observation in four showed some type of banding in this quadrant. The northeast quadrant was the least likely to have banding in any given observation; only about one observation in ten showed this type of pattern. Reference to Table A-III (Appendix A) shows that 10 of the 17 occurrences of banding in this quadrant were below 40N latitude and adjacent to the southeast quadrant. The two southern quadrants contained more than 75% of the occurrences of small banding, whereas they have about 59% of the total number of observations. The occurrences of large band size tend to be concentrated in the southeast quadrant which has 47% of the occurrences, but only 26% of all the observations.

The greatest likelihood of banding occurring during the 1962 period was again in the southeast quadrant (Table II). The probability of the cloud pattern occurring in this quadrant during the 1962 period was nearly 2.5 times greater than during 1961. The northward shift in the cloud pattern during the second year is shown quite clearly in the southwest quadrant. In this quadrant the percentage of observations in which banding was apparent decreased from 18%-11%. On the other hand, the northern half showed an increase in percentage from 12-36. A comparison of Tables A-III and A-VI reveals that the changes occurred within rather definite zones in these quadrants. Possible relationships between the changes in the Pacific Anticyclone for the two time periods and the changes in the cloud patterns are discussed in Appendix B.

3.4 COMPARISON OF SATELLITE AND SURFACE CLOUD OBSERVATIONS

The significance of the distributions of the amount of cloud cover on a synoptic scale as determined from satellite observations, and discussed in the previous section, can perhaps be made more meaningful if compared with surface observations during the same time periods. However, because of the restrictive nature of the satellite observations as to what constitutes an observation and the desire to work with only one type of cloud pattern, such comparisons cannot be made for the whole region. A comparison cannot be made at all for the northern half of the region because of the frequent presence of the polar front. The major factor which would affect such a comparison in the southern half of the region is the presence of tropical storms. Such tropical storms affect only a small portion of the total area and the number of occurrences in these two time periods was small so that the number of surface observations in these quadrants could not have a noticeable effect if allowed to remain in the set.

It was pointed out in the previous section that the frequency distributions of cloud amount differed between the southwest and the other quadrants. In order to make a more valid comparison of the two different types of observations, the surface observations were also separated into the same two subregions. The satellite observations were divided into nine groups, corresponding to the cloud amounts, by equally subdividing groups 2, 3, and 6.

The frequency distributions of the surface cloud observations made at 1800,0000 and 0600 GMT (primarily daytime) in the southeast and southwest quadrants as well as the satellite observations for both 1961 and 1962 periods are shown in Fig. 12. (Surface observations were not available for the sector enclosed by 30 to 35N latitude and longitude less

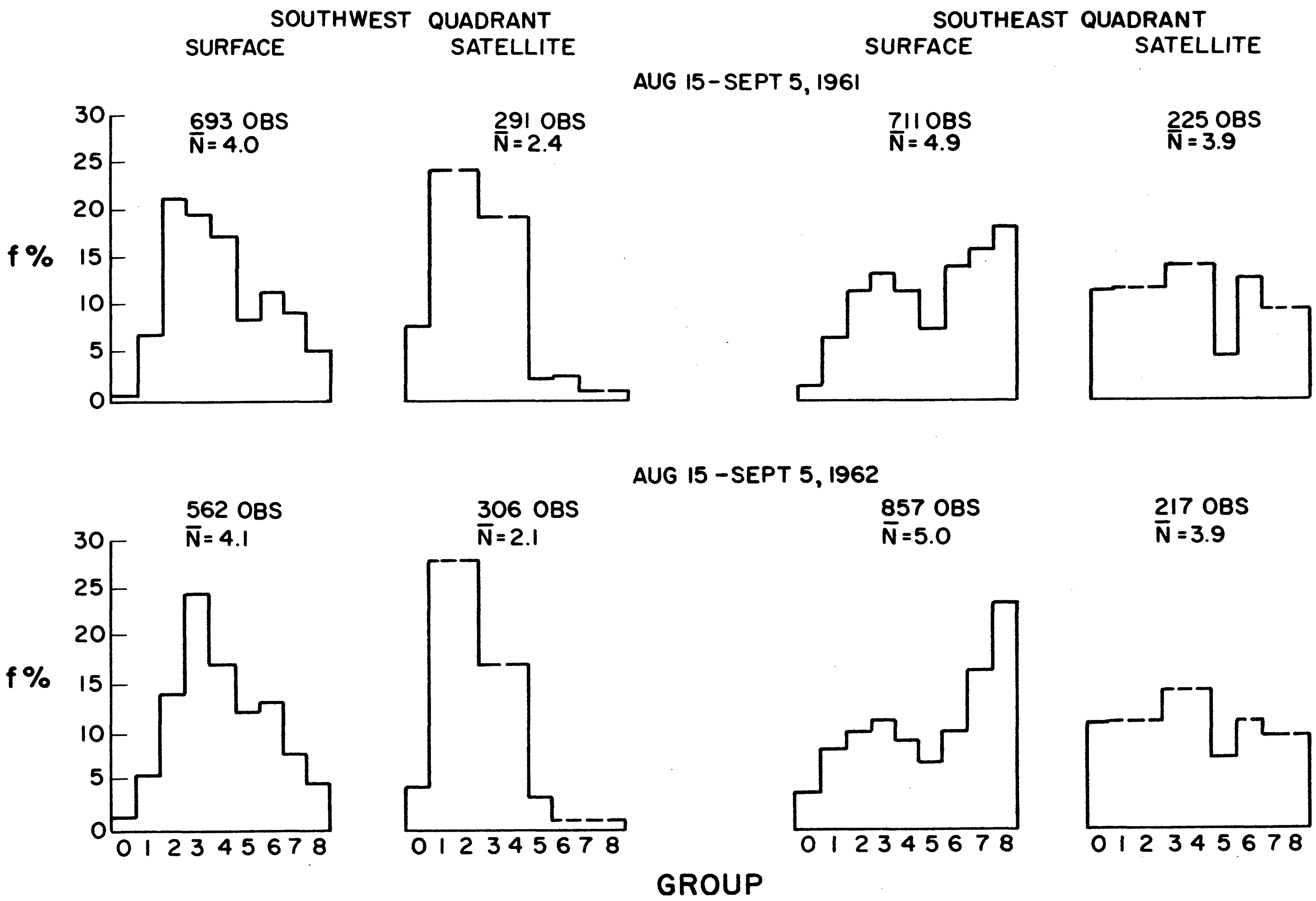

Fig. 12. Distribution of surface and satellite observations of cloud amount. ($\overline{N}$ is the average cloud amount in eighths.)

than 130W during the 1961 period.) A comparison of the mean cloud amount within a given quadrant and the same method of observations shows almost no change from the first year to the second. The largest change in the mean cloud amount was about 0.1 octa.

The frequency distributions show that the surface observations of low-level cumuliform clouds have a much greater frequency of occurrence of higher cloud amounts. This is to be expected. The southeast quadrant in each time period had a cloud amount of broken or greater ($\leq 6/8$) in approximately 50% of all the surface observations. By comparison only about 30% of the satellite observations showed a cloud amount of broken or greater. The southwest quadrant shows an even greater difference in these particular cloud amounts. The surface observations show 26% of the total had a cloud amount of broken or greater in this quadrant while only a little more than 4% of the satellite observations in the 1961 period had a cloud amount this large. In the 1962 period only 2% of the satellite observations in the southwest quadrant had a cloud amount of broken or greater.

Although the two methods of observing the cloud cover show completely different distributions of cloud amount, it is reasonable to expect that the mean of the two sets would, as the number of observations becomes very large, approach the same limit, i.e., the average amount of cloud cover. In reality, it was found that the same difference in the means as given by the two methods was maintained from the first year to the second.

The difference amounts to one octa in the southeast quadrant but increased to about 1.6 octa in the southwest quadrant. The surface observations show a mean cloud cover of approximately 50% in the southwest quadrant. The satellite observations give a mean value of only about 30%. A difference of 20% between the two types of observations is larger than would be expected if the true mean is less than 50% cloud cover, especially when one considers the large number of observations from which the mean values were computed.

The major factor contributing to the large difference in the two means involves not only the actual distribution of the cloud amounts as given by the two types of observations, but also the distribution of the cumulus cell sizes derived from the satellite observations (Fig. 11). The apparent bias in the cell size observations, discussed in the previous section, does not allow us to make comparisons from one year to the next. However, meaningful comparisons can be made among the different quadrants for observations made during the same time period. In particular, during the 1961 period, Fig. 11 shows that for observations that fit one of the four size categories, i.e., small, medium, large and mixed, approximately 41% were assigned to the class of small size and only 8% were given the value of large. This indicates that the cumulus clouds in the southwest quadrant show a much greater tendency to occur as small cells than as clusters which occur in the other quadrants. As individual cells they have a high probability of being smaller than the limit of resolution possible with the TIROS camera. This factor can also account in large part for the unique distribution of the cloud amount given by the satellite observations in this quadrant (Fig. 10).

The contribution of these very small cells to the overall cloud distribution can also be seen by comparing the distribution of observations containing very few or no clouds, i.e., cloud amounts 0 and 1 in Fig. 12. Since the area extent of one satellite observation as it is defined takes in a much larger area than a surface observation, the number of cases with clear or very few clouds could be expected to be less for this type of observations. The actual distributions show very definitely that the opposite is true. In fact, were the clouds to occur exclusively in groups larger than the limiting resolution of the TIROS cameras and have a mean cloud amount of 50%, the surface observations would show a nearly uniform distribution for the number of observations in each cloud amount. The southwest quadrant shows deficiencies at each end of the scale in this respect with the surplus concentrated in the cloud amounts from 1/4 to 1/2.

The distribution of the cell size in the satellite observations, as well as the distribution of the cloud amount given by surface observations, both point to the fact that observations of cloud amount obtained from satellites can yield an estimate which is too low for the low-level cumuliform cloud patterns. A counter-argument is that the satellite cloud observations used for this study are not a representative sample of the cloud cover, especially in the southwest quadrant. No estimate is available of the areas on the videographs which were thrown out because they did not meet the requirements for a cloud observation. The importance of this factor can therefore, not be determined. However, the comparison of the satellite observations with the surface observations has also served to clear up quite a mystery which occurred while recording the satellite observations. The videographs made over the southwest quadrant frequently appeared to be of inferior quality in the contrasts shown by the gray scale as compared to the videographs taken over the other regions. Many of the pictures, although apparently quite free of cloud cover, contained very little contrast between the water and the cloud present. It is now quite clear that this low contrast was the result of integrating very small and unresolvable cumulus clouds with the very dark background of the water.

4. SYNOPTIC DATA

4.1 EASTERN NORTH PACIFIC CLIMATOLOGY

The Pacific Anticyclone dominates the eastern north Pacific in summer. It forms part of a network of semi-permanent circulation patterns over the globe sometimes referred to as "centers of action." The name refers to each being the center of rotation for major weather systems. The extra-tropical cyclones move on a path around the northern periphery and the tropical storms follow the principal track from east to west around the southern extremity. The mean position of the center of the anticyclone for the month of August (Fig. 1) is near 38N, 149W with a central pressure of 1027 mb (U.S. Navy, 1956).

Numerous studies have been made of this semi-permanent system at various seasons of the year, especially in attempting to assess its role in the general circulation. Calculations of the air transport over this region for each month of the year were done by Werenskiold in 1922. For the month of August, his analysis shows the center of the anticyclone located at about 43N, 145W, more than 300 mi northeast of the position given above. His analysis of the streamline field shows the northeastern part of the region has southwesterly winds during the month of August. More recent analysis shows west to northwest winds in this area indicating a smaller angle of cross-isobar flow than Werenskiold's analysis.

The transfer of energy between the ocean and the atmosphere in the form of latent and sensible heat has been studied in varying degrees of detail on a climatological basis. (Cf. Jacobs, 1942, 1943, 1951). The maximum values for the rate of exchange of both sensible and latent heat on an annual basis occurs near latitude 20N between the Hawaiian Islands and North America with the peak values near 150W. The latent heat exchange rate is approximately an order of magnitude larger than the rate of exchange of sensible heat when averaged over a 12 month period. Over the Northeast Pacific Ocean the annual values of the rate of energy loss from the sea surface through evaporation vary from 100-300 cal cm^{-2} day^{-1}.

During the summer months the rate of exchange of sensible heat from the ocean to the atmosphere approaches zero in the latitude zone of 35-40N, and reverses sign to the north. The rate of exchange of sensible heat between the ocean and the atmosphere is generally less than 20 cal cm^{-2} day^{-1}.

Unquestionably, the region of the anticyclone subjected to the most detailed investigations has been the southeast quadrant or the region of the Northeast Trade winds including the west coast of the United States and the Hawaiian Islands. The two most detailed investigations of the atmospheric conditions existing over this region during the summer months are those of Riehl, et al. (1951) and Neiburger, Johnson and Chien (1961). Riehl, et al., give a detailed analysis of the conditions existing between California and Hawaii during the summer of 1945 while the analyses presented by Neiburger, Johnson and Chien represent a composite of all available data over the whole region.

The most noteworthy feature of this region is the persistent occurrence of the trade or subsidence inversion. The average height of the inversion varies from about 400 m near the coast of California to more than 2000 m in the vicinity of the Hawaiian Islands. Neiburger, Johnson and Chien constructed a vertical cross section (Fig. 13) from San Francisco to Honolulu which shows the inversion as a distinct feature. In determining the mean values for the cross section, the base and top of the inversion were included as observation points.

The formation of the inversion is ascribed to the combined effects of subsidence in the northerly flow around the eastern part of the anticyclone and turbulent convection in the surface layers of the trade winds. The increase of this inversion height downstream is attributed to the result of cumulus convection penetrating the inversion and mixing of moist air with the very dry air which has subsided (Riehl, et al., 1951). Such a modification process has been studied in detail over coastal Southern California by Edinger (1963). The heating from below was found to modify the inversion so much that convective elements originating at the ground are able to escape from the marine layer and rise into the warm dry air above.

The inversion is present over the southeast quadrant on more than 75% of the observations. In particular, during the month of August, an inversion is found below 800 mb at the Weather Ship "N" (30N, 140W) on approximately 95% of the observations. According to Neiburger, Johnson

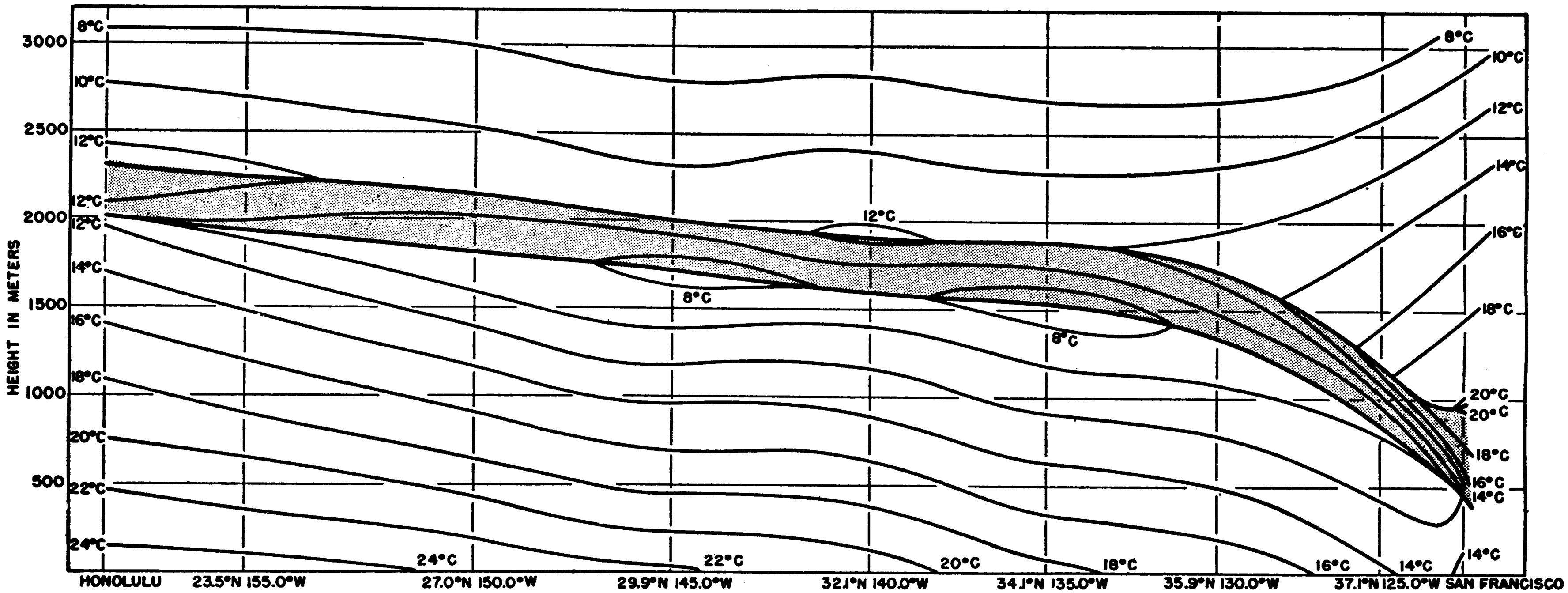

Fig. 13. Vertical cross section from San Francisco to Honolulu showing the temperature distribution and the height of the subsidence inversion (Neiburger, Johnson and Chien, 1961).

and Chien the frequency of occurrence of this inversion drops sharply to the west of Hawaii and also in the northeastern quadrant. No information is available on the frequency of occurrence of low-level inversions in the northwestern quadrant.

This brief summary of conditions found in the eastern part of the North Pacific Ocean points out that the relatively simple pattern exhibited by an analysis of the mean surface pressure masks a much more complicated pattern of other variables, such as those resulting from air-sea interactions. Some details of the synoptic conditions which prevailed during the two time periods of this study are discussed in Appendix B.

4.2 ANALYSIS PROCEDURES

Optimum procedures for a synoptic analysis in a study of this type would involve the use of surface and upper air observations made at the same location and time as the satellite observations of the cloud patterns. In this section and the one following a discussion is given of the procedures actually used to obtain the values of the meteorological variables.

A relatively large number of surface meteorological observations are available from this area, but they tend to be concentrated into the two shipping lanes. One connects California and Hawaii and the other runs between the West Coast of the United States and the Far East. Upper air observations in this region are available on a regular basis from two stations in Hawaii, Midway Island, two weather ships ("N," 30N, 140W; and "P," 50N, 145W), and dropsondes from regular weather reconnaissance flights. Sporadic upper air observations are also available from ships traveling through the region. The eastern boundary of the region is adequately covered by upper air observations taken along the west coast of the United States and Canada while observations taken over Alaska can be used to aid the upper air analysis along the northern boundary. Regular observations near the southern boundary are provided only by Johnston Island in the southwest. Wake Island and the weather ship "V" (31N, 164E) serve as a small aid in the upper air analysis along the western boundary, but a great reliance must also be placed on the surface analysis for assistance in analyzing an 850 mb chart over this part of the region.

The basic surface variables obtained from shipboard meteorological observations are pressure, air temperature, dewpoint temperature, and water temperature. The quality of these observations often leaves much to be desired. Undoubtedly, the least reliable of the four is the water temperature. Saur (1963) made a comprehensive study of the differences between water temperatures reported in the Log of Ship's Weather Observations and specially observed sea-surface temperatures. He found that the differences not only vary from ship to ship but also exhibit a large degree of variability between trips of a given ship, or even during a trip. He concludes that the water-temperature data currently reported are for the most part adequate only for general climatological studies. The observations of air temperature may also contain a bias depending on the exposure of the sensor aboard the ship. The exact nature of this bias is made even more complex by variability related to such factors as the time of day, cloud cover and wind speed. The bias in the air temperature can also be expected to affect the dewpoint temperature and this effect can also be ascertained in a qualitative sense only.

In order to use the three different temperatures on a synoptic basis in this study, special procedures were used to obtain the analysis of the isotherm pattern over the region. In the case of water temperatures, the 1200 GMT observations for three different days were plotted on the same map and the analysis was assumed to be valid for the three days. Although the same quantity of data could be obtained by using all the observations at the four different times each day, the method used has the advantage of spreading observations from the same ship over a larger area, and makes it easier to detect persistent errors in the observations from a given ship. It has been suggested that large-scale water temperature patterns remain more or less stationary for periods on the order of weeks (Perlroth and Simpson, 1962). Perlroth (1962) used this as a basis for studying the movement of a hurricane in relation to the water temperatures by using observations taken over a period of three weeks. On the latter basis it could be argued that a single analysis, based on all the observations of the water temperatures taken during the three-week period, would have been appropriate. However, in a statistical study, such as this, it is more important to avoid inducing a bias through errors in the analysis. Thus, even though the individual observations cannot be specified with the same degree of accuracy, the use of several analyses of water temperatures during the three-week period allows the possibility of averaging out errors in any specific analysis and should yield a more accurate set of observations.

The isopleths of the air- and dewpoint temperatures were drawn on a daily basis. Observations of these parameters made at 1800 GMT the previous day, as well as the 0000 and 0600 GMT observations of the day to be analyzed, were plotted on the same chart. During the analysis the 0000 GMT observations were subjectively weighted more than the other two times to achieve a distribution valid at 0000 GMT. Since the observations of air temperature were almost all made in the daytime any bias in these would most likely be that the temperatures are too high due to radiational heating of the ship in areas of few or no clouds. This would have the effect of increasing the spread between the air and dewpoint temperature.

It was felt that no improvement could be achieved in the six-hour continuity available in the Northern Hemisphere Surface Analysis completed by the National Weather Analysis Center, and therefore, the 0000 GMT analysis was used to obtain the surface pressure.

All available observations of 850 mb data for 12 hr on either side of 0000 GMT were plotted on the same chart. The analysis was performed in such a manner as to achieve a distribution of the observed 850-mb height pattern valid at 0000 GMT.

Values of the temperature variables were read at grid points spaced at 200 km intervals over the region. The surface pressure and the height of the 850-mb surface were each read at latitude-longitude grid points of two degrees spacing to facilitate computation of the east-west and north-south components of the geostrophic wind.

Errors of analysis are bound to occur, and may on occasion be quite large, especially when the spatial derivative of the variable is large. Another source of error which may be substantial is that of defining the position of the center of the cloud observation. This may be expressed as,

$$e_t = e_s + E_p \cdot \nabla S$$

where

e_t = the total error,

e_s = the error in the analysis of the synoptic variable S, and

E_p = the vector error in the position of the cloud observation.

In general, E_p is of finite size and, therefore if ∇S is large, the second term will tend to dominate the right hand side of the above expression. In other words, the greater the gradient of a synoptic variable across the area, the less significant are the inaccuracies of the individual parameters.

4.3 SYNOPTIC VARIABLES

Most of the synoptic parameters used in the statistical analysis are composed of various linear and nonlinear combinations of the four primary surface variables discussed in the previous section. The 22 used in this study of the low-level cumuliform cloud patterns together with the units of each and the abbreviations assigned are given in Table III. While those used do not exhaust all possible linear and nonlinear combinations of the original variables, it is believed to be a fairly comprehensive list of those parameters for which some physical basis for their role in the formation of convective cloud patterns over the ocean may be argued. The remainder of this section is concerned with a discussion of the methods used to determine the values for the list of variables.

Latitude and longitude were included as "synoptic variables" to help interpret climatological tendencies in both the synoptic and cloud data. The frequency distributions of the cloud observations presented in Section 3.3 have shown that specific cloud patterns are favored in one quadrant over another. Many of the synoptic variables show large gradients over the region. In the relatively stationary conditions of the Pacific Anticyclone it is convenient to use the geographical coordinates rather than a relative system from the center of the anticyclone.

During the three weeks in which the observations were taken the Greenwich mean time for them is spread over a 12-hr period during the day. Using mean solar time as a reference this time period is reduced to 8 hr.

TABLE III

SYNOPTIC VARIABLES USED IN THE STATISTICAL ANALYSIS

Abbreviation	Variable	Units
LAT	Latitude	degree
LNG	Longitude-100	degree
THR	Mean solar time	hour
Z85	Deviation of computed 850-mb height from observed	m
VGS	Surface-geostrophic wind speed	$msec^{-1}$
TSD	Air-dewpoint temperature difference	°F
TWS	Water-air temperature difference	°F
TWD	Water-dewpoint temperature difference	°F
U	U-component of wind speed	$msec^{-1}$
V	V-component of wind speed	$msec^{-1}$
LTH	Latent heat flux	cal m^{-2} sec^{-1}
SNH	Sensible heat flux	cal m^{-2} sec^{-1}
DIV	Horizontal divergence	sec^{-1}
VSHR	Magnitude of vector difference in wind between 850 mb and surface	$msec^{-1}$
SHR	Scalar difference in wind between 850 mb and surface	$msec^{-1}$
FRE	Free-convection	(non-dimens)
FOR	Forced-convection	$msec^{-1}$ K^{-1}
COMB	Combined free and forced convection	$msec^{-1}$
RICH	Modified Richardson number	K m^{-2} sec^{2}
ZR	Relative vorticity	sec^{-1}
ZA	Absolute vorticity	sec^{-1}
DTN	Thermal gradient normal to the surface wind	K km^{-1}

An 850-mb height field was computed from the surface pressure and temperature. It was assumed that an adiabatic lapse rate existed between these two levels. The deviation of the computed value from the observed 850-mb height field, estimated to the nearest 10 m, was used as an index of the stability of the air in this layer. It would be highly unwarranted to claim that any given observation actually attains the accuracy of ±10 m. Indeed, the accuracy claimed for the determination of the height of the 850-mb surface from an actual upper air sounding is only this amount (U.S. Weather Bureau, 1963). The accuracy of a specific observation will be in a large part dependent upon the location within the region. In particular, the northwest quadrant of this region can be expected to suffer the greatest inaccuracies not only because of the great paucity of observations, but also due to the large day to day changes in the height pattern which take place there compared to the other quadrants.

The three observed temperatures, air, dewpoint, and water, can be combined to form three temperature differences only two of which are independent. The air-dewpoint and air-water temperature differences were the two used in the statistical analysis to the virtual exclusion of the dewpoint-water temperature difference. The list given in Table III is reduced to 21 as the maximum number which can be used in the statistical analysis at once due to the linear relationship among the variables TSD, TWS, and TWD.

The geostrophic approximation was used to determine the wind speed, and its easterly and northerly components, from the surface pressure field and the 850-mb height field. This approximation was justified since it comprises a finite difference over an interval of 6° latitude for the east-west component and 6° longitude for the north-south component. The method can therefore be relied upon to give a more representative single wind estimate over the area of a cloud observation than could an analysis of the observed wind field. The surface geostrophic wind speed would, except for calm conditions, result in an overestimate of the observed wind. Based on previous investigations, the overestimate is a function of the wind speed. Sheppard and Omar (1952) found that the ratio of the observed to the geostrophic wind speeds at the surface, over the islands of Wake, Johnston and Eniwetok in the Pacific, varied from slightly less than 0.5 for low wind speeds to approximately 0.75 for high wind speeds. The increase of the ratio with wind speed was well defined at all stations. The mean angle between the surface wind and the isobars varied from 10-17°. In a study of west winds over the ocean, Sheppard, Charnock and Francis (1952) found the ratio of the surface wind speed to the geostrophic was approximately 0.77 for one method and 0.88 for a second method. The former results were determined by using hourly values of pressure from three triangular arrays of pressure-reporting stations to compute the geostrophic wind speed. The other method utilized hourly synoptic charts.

Neiburger, Johnson and Chien (1961) vehemently criticize discussions of the pattern of air flow over the surface of the oceans based on deductions concerning the geostrophic wind corresponding to the pressure, especially in the region of the Pacific Anticyclone. They particularly point to the southwest quadrant of the anticyclone as a region where the streamlines are about 45° from the isobars, with northeast flow observed where the isobars run east-west. Their streamline analysis appears to give directions with too large a northerly component. An examination of wind rose data (U.S. Navy, 1956) shows that a resultant wind direction during the month of August would be between east and east-northeast. The angle between the streamlines and the isobars would therefore be at most 20°, in closer agreement with results determined on an hourly basis. The easterly and northerly components as well as the total wind speed at the surface have been included as separate variables. The same variables for the 850-mb surface were not included separately. Instead, the difference between the 850 mb and the surface values were included. The two variables included were the scalar difference (SHR) and the magnitude of the vector difference (VSHR) between the wind speeds at the two levels.

The two variables of wind difference between the surface and 850-mb level give the actual value of the wind shear only in the special case where the wind varies linearly between the two levels. The non-linear variation of the wind with height was found by Kuettner (1959) to be especially important in the formation of cloud bands. The wind maximum within the convective layer associated with cloud lines would occur between the surface and 850-mb levels, if it is present at all. Since this study utilizes the geostrophic approximation, the wind profile would not show an increase of speed with height in the lower portion as a result of decreasing friction. Instead, the maximum wind speed would occur at the surface, and decrease upward as a result of the thermal wind component.

In order to determine whether or not the maximum geostrophic wind speed was occurring at the surface, the temperature gradient normal to the surface wind was computed. This computation involves the transformation of axis from a latitude-longitude coordinate system to the natural coordinates along and perpendicular to the flow as shown in Fig. 14.

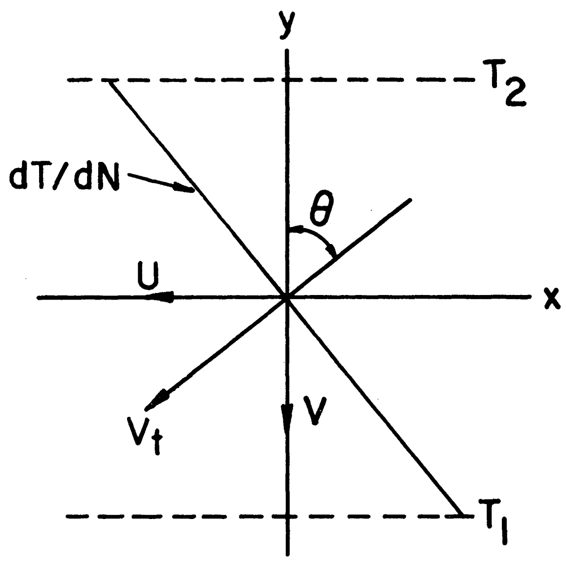

Fig. 14. Transformation from x,y (latitude and longitude) to natural coordinate system.

The temperature gradient normal to the flow is given by:

$$\frac{dT}{dN} = \frac{\delta T}{\delta x} \cos \Theta + \frac{\delta T}{\delta y} \sin \Theta \tag{2}$$

where δx and δy are approximated by 4° latitude and longitude, respectively. This can be written in terms of the wind speed as

$$\frac{dT}{dN} = \frac{\delta T}{\delta x}\frac{V}{VGS} + \frac{\delta T}{\delta y}\frac{U}{VGS} \qquad (3)$$

where U, V and VGS are as given in Table III.

The surface pressure field is converted to a 1000-mb height field by using the empirical pressure-height relationship that 100 ft represents 3.75 mb at this level of the atmosphere. The geostrophic vorticity on the 1000-mb surface is then computed for each grid point by adapting Fjortoft's graphical technique as outlined by Petterssen (1956) to an electronic computer program.

If we neglect the "tipping terms" the vorticity equation for a constant pressure surface can be written as:

$$\frac{D(\xi+f)}{Dt} = -(\xi+f)\,\nabla_p \cdot V \qquad (4)$$

where

$$\frac{D}{Dt} = \frac{\partial}{\partial t} + V \cdot \nabla_p ,$$

ξ is the relative vorticity, f is the Coriolis parameter, and ∇_p represents the two-dimensional del operator on a constant pressure surface.

The horizontal divergence on a constant pressure surface can be determined from this equation in the following manner:

$$\nabla_p \cdot V = -\frac{1}{\xi+f}\left(\frac{\partial\xi}{\partial t} + u\frac{\partial\xi}{\partial x} + v\frac{\partial\xi}{\partial y} + v\frac{\partial f}{\partial y}\right). \qquad (5)$$

The local rate of change in this expression was approximated by the change in vorticity at the grid point during the previous 24-hr period. In order to evaluate the advection terms, it was assumed that the instantaneous values were representative. It is anticipated that these two approximations should be quite representative except for some cases of rapid changes in the northwest quadrant where a time period of 24 hr for the local rate of change of the vorticity is much too long. The three variables derived from these computations were the relative vorticity (ZR), absolute vorticity (ZA) and the horizontal divergence on the 1000-mb pressure surface (DIV).

The accuracy with which it is possible to compute the voriticity and the horizontal divergence cannot be specified in a quantitative manner. On a comparative basis however, it is possible to state that the vorticity will be computed less accurately than the wind field and the horizontal divergence even less accurately than the vorticity. All three quantities involve the numerical differentiation of the original pressure or height field. Specifically, the computations for the geostrophic wind speed utilize only the first derivatives of the height field. The manner in which the horizontal divergence was computed involves the third derivatives of the height field. An inspection of the vorticity and divergence values obtained in regions of strong flow patterns showed agreement in sign with what would be expected. In the case of the divergence especially, the usual values obtained in this Pacific Anticyclone are small. Thus, it is very difficult to specify whether or not such values have any meaning and even whether or not the sign of the divergence is significant.

Two other parameters which should prove important, at least in determining the amount of cloud cover, are the transfer of sensible and latent heat between the ocean and the atmosphere. The availability of useful methods for the practical determination of these quantities is however, still an open question. For a detailed review of this problem, see Munn (1960), Deacon and Webb (1962), and Malkus (1962). Using specific humidity, which can readily be converted to latent heat, a general equation for the diffusion of this quantity is:

$$\frac{Dq}{Dt} = \nabla \cdot K \nabla q \tag{6}$$

where

q = the specific humidity, and

K = the transfer coefficient for the quantity q.

In order to evaluate Eq. (6), it is usually assumed:

1. A mean wind $\bar{u}$ can be defined for a suitable time interval.

2. $\bar{v} = \bar{w} = 0$.

3. Diffusion in the forward direction is negligible in comparison with forward transport by the mean wind, i.e.,

$$\frac{\partial}{\partial x}\left[K_x \frac{\partial q}{\partial x}\right] \ll \bar{u}\,\frac{\partial q}{\partial x}$$

4. Steady state conditions exist, i.e.,

$$\frac{\partial q}{\partial t} = 0.$$

5. All lateral derivatives are zero and thus the problem is reduced to two dimensions.

6. The transfer coefficients for momentum, sensible heat and water vapor are equal, i.e.,

$$K_M = K_S = K_E = K \ .$$

With these restrictions Eq. (6) becomes

$$\bar{u}\ \frac{\partial q}{\partial x} = \frac{\partial}{\partial z}\left[K\,\frac{\partial q}{\partial z}\right] \tag{7}$$

Sverdrup (1957) made two further assumptions, i.e., the gradient of the specific humidity in the horizontal direction can be neglected and that the flux of water vapor is independent of height z in the region 10-20 m above the sea surface. The flux F is then given by

$$F = K\,\frac{dq}{dz} = \text{constant} \tag{8}$$

If the flux is upward there is evaporation and

$$E = -\,K\,\frac{dq}{dz} \tag{9}$$

where E is the evaporation.

Making use of the sixth assumption above, K may be written

$$K = k_o u_* z \tag{10}$$

where $k_o = 0.4$ (von Karman's constant), u_* is commonly called the friction velocity given by

$$u_* = (\tau/\rho)^{1/2} \qquad (11)$$

in which case τ is the shearing stress and ρ is the density. τ can be written in terms of the drag coefficient C_D:

$$\tau = \rho \, C_D \, u_z^2 \, . \qquad (12)$$

Substituting (11) and (12) in (10), the expression for K is

$$K = k_o \, C_D^{1/2} \, u_z \, z \qquad (13)$$

where the subscript o refers to the surface and z to the level of measurement.

Montgomery (1940) examined evaporation from sea surfaces and concluded that the humidity could be specified in terms of an evaporation coefficient, viz:

$$\Gamma_z = - \frac{1}{q_o - q_z} \frac{dq}{d(\ell n \, z)} \, . \qquad (14)$$

Substituting (13) and (14) into (9) the evaporation can be written as:

$$E = k_o \, C_D^{1/2} \, u_z (q_o - q_z) \Gamma_z \, . \qquad (15)$$

The choosing of a value for Γ_z poses some difficulty. The problem has been discussed in some detail by Sverdrup (1951). He favors the assumption that next to the sea surface there exists a thin layer, the thickness of which is inversely proportional to the wind velocity, through which water vapor is transported upward by molecular diffusion. Above this layer eddy diffusion transports the water vapor. This argument seems reasonable for a fairly smooth surface; but since the sea is rarely smooth it presents some difficulties. Sverdrup assumed that essentially the same process takes place even when the sea surface is rough. If a small air parcel hits the surface, it may lose all its momentum, but it will not immediately reach the specific humidity of the surface. If it remains at relative rest in one of the depressions of the rough surface its water vapor content will increase due to molecular diffusion. This means that essentially a process similar to that occurring over a smooth sea surface will prevail provided that a statistical diffusion layer is considered to exist.

Montgomery (1940) makes a different assumption. His final results for the evaporation are low in comparison to rather crude observations that have been carried out, whereas Sverdrup's theory gives results closer to the observed values for evaporation.

Riehl, *et al.* (1951) used Eq. (15) in the form:

$$E = 1.71 \times 10^{-6} (q_o - q_z) u_z \quad . \tag{16}$$

The flux of latent heat is given by

$$Q_e = LE \tag{17}$$

where L is the latent heat of vaporization. For the range of temperatures used the value of L is nearly constant at approximately 585 cal/gm.

The latent heat transfer is then determined from

$$Q_e = (q_o - q_z)u_z \times 10^{-3} \text{ cal cm}^{-2} \text{ sec}^{-1} \qquad (18)$$

where u_z is measured in cm/sec and q_o, q_z in gm/kg.

By reasoning similar to that given for latent heat transfer the flux of sensible heat can be written

$$Q_s = \rho C_p C_D(T_o - T_z)u_z \qquad (19)$$

where C_p is the specific heat at constant pressure, and T_o, T_z are the temperatures at the surface and at the height z. Substituting values into this equation gives

$$Q_s = 4.16 \times 10^{-7} (T_o - T_z)u_z \text{ cal cm}^{-2} \text{ sec}^{-1} . \qquad (20)$$

Equations (18) and (20) assume that the magnitude of the heat transfer is independent of the vertical density stratification. In other words, should the gradient of specific humidity be negative in Eq. (18) the condensation of water vapor onto the sea surface would proceed at the same rate as the evaporation rate when the gradient is opposite. Likewise, a negative temperature gradient in Eq. (20) indicates a sensible heat transfer from the atmosphere to the ocean at the same rate as the transfer in the opposite direction. Discussions of these cases by Manier and Moller (1961), and Laevastu (1963) indicate that this is not the case in the real atmosphere. Tisdale and Clapp (1963) refer to a communication from Prof. Herbert Riehl in which he discussed the possibility that the coefficient of sensible heat exchange approaches zero in individual cases when the air temperature is higher than that of the sea.

Laevastu has proposed the use of different formulae for both the latent and sensible heat transfer computations when the gradient reverses sign. However, he concedes the lack of any direct proof for the validity of these formulae and one must rely on reasoning only. It was considered that for the purpose of this study the use of different formulae based on the sign of the gradient was not warranted and thus the assumption is made that the magnitude of the transfer rate for both sensible and latent heat are independent of the sign of the gradient.

In computing the latent heat transfer with Eq. (18), it was assumed that saturated conditions prevail at the sea surface. Thus, q_o refers to the saturated specific humidity value for the temperature of the sea surface. The Smithsonian Meteorological Tables were used to obtain the q_o's and q_z's (List, 1958).

The variables discussed up to now have consisted of quantities for which physical reasoning would suggest should be important in atmospheric convection over the ocean. The purpose of the variables FOR, COMB, and RICH is an attempt to classify the predominant type of convective motions associated with the cumuliform cloud patterns. The definitions of these motions are taken as follows (Huschke, 1959): convection is free if the motion of the fluid in the gravitational field is maintained solely by differences in density caused by local temperature inequalities; forced convection means that the motion of the fluid is due to an applied external force.

The layer in which the convective motion takes place has a limited vertical extent. In order for clouds to form, the rising air must attain saturation prior to reaching the top of the convective layer. The amount of cloud cover should therefore be related to the relative humidity of the air in the surface layers independent of the type of convection. Specifically, it should be inversely proportional to the air-dewpoint temperature difference.

The buoyancy a parcel can attain for free convection in the surface layers is directly proportional to the water-air temperature difference. Forced convection on the other hand is primarily due to an applied pressure gradient force or directly proportional to the wind speed. Free convection (FRE) is then determined by:

$$FRE = \frac{TWS}{TSD} . \tag{21}$$

The parameter used for forced convection (FOR) is a simple ratio between the surface wind speed and the air-dewpoint temperature difference, i.e.,

$$FOR = \frac{VGS}{TSD} . \tag{22}$$

The values in Eq. (21) can have either sign indicating positive and negative buoyancy. In most cases the magnitude of the ratio will be less than one. The smallest value of the ratio in Eq. (22) is zero and with very few exceptions the value should be less than ten. In both Eqs.

(21) and (22) the lowest value of the denominator was assumed to be one.

In all probability the convective motions taking place over the ocean are not susceptible to such a simple classification as either free or forced. A parameter was derived to take into account the combination of the two types of motion. This parameter (COMB) was formed as a ratio:

$$\text{COMB} = \frac{\text{VGS x TWS}}{\text{TSD}} \quad . \tag{23}$$

Equation (23) can have either sign and can have a much larger range of magnitude than either Eqs. (21) or (22). The lowest value for TSD when used in Eq. (23) was assumed to be one.

The criterion usually used for the onset of turbulent flow in the atmosphere is a parameter known as the Richardson number which can be written as:

$$\text{Ri} = \frac{g}{\theta}\frac{\partial\theta}{\partial z}/(\frac{\partial\bar{u}}{\partial z})^2 \tag{24}$$

where

g = the acceleration of gravity,

θ = the potential temperature,

z = height, and

$\bar{u}$ = the mean velocity.

Since the surface wind speed is computed from the pressure field, this quantity and the air temperature are determined at the same level above the sea. The wind speed at $z = 0$ is exactly zero. The ratio of the water-air temperature difference and the total wind speed squared was used as a variable called the modified Richardson number:

$$\text{RICH} = \frac{\text{TWS}}{(\text{VGS})^2} \quad . \tag{25}$$

Calm winds were assumed to have a numerical value of 1 m/sec when used in Eq. (25).

In the discussion of the synoptic-meteorological variables just concluded an effort was made to point out some of the deficiencies in the data. All the meteorological variables involve a finite difference approximation to a differential. Differentiation is a diffusion process in contrast to the smoothing achieved by integration. The most general statement that can be made about the quality of the synoptic variables list in Table III is the following: By assigning the lowest number to the best quality, the attributes of a specific variable are directly proportional to the order of the finite difference equation used in determining its value.

5. CLOUD PARAMETERS AS DEPENDENT VARIABLES

5.1 MULTIPLE-DISCRIMINANT ANALYSIS

The technique of multiple-discriminant analysis was used to select the synoptic-scale parameters statistically important in determining the different types of cloud patterns. A major advantage of using this method of statistical analysis is that the variables to be specified need not be ordered, but can be classified into groups. The overlying principle in the analysis is that of statistical specification of the cloud variables, using the synoptic data as predictors (or better, specifiers) and no time lag. This study utilizes the modifications, described by Miller (1962), to the method of discriminant analysis originally developed by R. A. Fisher.

Multiple-discriminant analysis screens from a set of "predictors" a subset that efficiently discriminates between two or more "predictand" groups. It is possible to achieve a further reduction in dimensions by determining several linear combinations of predictors that will discriminate without any loss of efficiency. The discriminant function Y_j is then defined as:

$$Y_j = \sum_{i=1}^{P} V_{ji} X_i \qquad (26)$$

where the X's are predictors selected by the screening discriminant analysis and the V's are weights obtained by a technique which assures that the linear combination Y_j is a better discriminator than any other possible linear combination of the X's.

The criterion used for screening the predictors in Eq. (26) is one which maximizes the distance between the vector means of the discriminant function and minimizes the spread of the points about the vector means. The ratio of the sums of squares between groups over the sums of squares within groups for values of the discriminant function is a measure of the ability to discriminate between groups. This value λ_1 is given by:

$$\lambda_1 = \frac{SSB\ Y_1}{SSW\ Y_1} \quad . \tag{27}$$

The statistical criterion used for determining the significance of a predictor S selected by the screening discriminant analysis is

$$(D_S^2 - D_{S-1}^2) > \chi^2(\alpha^*/P), \quad (G-1) \tag{28}$$

where

$$D_S^2 = (n\text{-}GxS) \text{ trace } W^{-1} B(X^{(1)}\ldots X^{(S)}) \tag{29}$$

in which case

n = one less than the total number of observations in the sample,

G = number of groups.

Trace $W^{-1} B(X^{(1)}\ldots X^{(S)})$ is the sum of the diagonal elements of the matrix formed from the product of the inverse of the matrix of sums of products within groups (W) times the matrix of sums of products between groups (B) and where the predictors $X^{(1)}\ldots X^{(S-1)}$ have already been chosen. The specific predictor S chosen from among the (P-S) possible predictors is that one which maximizes this trace of the matrix.

$\chi^2_{(\alpha^*/P)}$ is the critical value of χ^2 with a true level of significance given by α^*, but which has been corrected for the probability of selecting a predictor by chance by dividing the desired level of significance by the number of predictors (P) from which it was possible to select the predictor S. The number of degrees of freedom for χ^2 is (G-1). The .05 level of significance is used throughout this report as the value of α^*.

The weights V_{ji} in Eq. (26) are the eigenvectors associated with the latent roots of the determinantal equation

$$|W^{-1}B-\lambda I| = 0 \qquad (30)$$

where the matrices W and B are as given in Eq. (29), I is an identity matrix and the eigenvalues are as given in Eq. (27). The procedure described by Cooley and Lohnes (1962) for determining the eigenvalues and eigenvectors of a nonsymmetric matrix of the form $C = (W^{-1} B)$ was used. Their method involves determining the roots and vectors of the matrix C by successive diagonalization of two real symmetric matrices.

The maximum number of discriminant functions [Eq. (26)] is given by min (G-1, PP), where G is the number of groups and PP is the number of predictors selected.

Probabilities can be assigned to occurrences of the groups of the predictand by computing the Euclidean distance between observations in the discriminant space and then choosing the h closest points (Miller, 1962). The ratio of the observed frequencies in each of the groups to the total number h determines estimates of the conditional probabilities for the occurrence of each group. The group specified is the one having the maximum probability of occurrence. The value of $h = 25$ was used in this study.

The computations for the analysis were made using a computer program written to (1) normalize the values of the set of synoptic parameters, (2) perform the screening analysis for selecting the significant predictors, (3) compute the values of the discriminant functions, and (4) determine the conditional probabilities for occurrences of each group using the dependent or an independent sample.

The results obtained from the discriminant analysis are presented in the remainder of this section. Section 5.2 is concerned with the discrimination among groups of different cloud amounts. The results for cumulus cell size and band spacing are discussed in Sections 5.3 and 5.4, respectively.

The analysis makes use of a set of synoptic parameters of nonuniform quality. A complex variable composed of the product of several of the simpler parameters can be expected to have a larger error than any of the simple ones. In the same manner, a synoptic variable which involves the differentiation of a more basic parameter would also be of inferior quality. In interpreting the results of the multiple discriminant analysis, the complex variables which appear high on the list for possible selection will be pointed out even though they may not be selected.

5.2 DISCRIMINATION AMONG GROUPS OF CLOUD AMOUNT

5.2.1 Predictors Selected in the Screening Analysis

An analysis of the observations of cloud amount for the 1961 period was made using six groups. A similar analysis was performed on the same set of observations after they had been combined into three groups made up individually of the two categories on each end of the six and the two in the middle.

In the screening analysis using six groups there were five synoptic parameters selected which may be considered significant. When the observations were combined into three groups the screening selected six variables above the minimum level for statistical significance. The particular variables selected together with other information pertinent to their use in the discriminant functions are presented in Table IV (6 groups) and Table V (3 groups).

TABLE IV

SELECTED PREDICTORS FOR SIX GROUPS OF CLOUD AMOUNT

X_i	$(D_S^2-D_{S-1}^2)$	$\chi^2_{.05}/P$	V_{1i}	V_{2i}	V_{3i}	V_{4i}	V_{5i}
LAT	132.0	19.2	-.69	.40	-.26	-.68	-.26
LNG	103.2	19.1	.67	-.08	.41	-.50	-.23
LTH	37.6	18.9	.003	.82	.004	.12	-.38
TSD	22.9	18.7	.29	.10	-.82	-.52	.35
SHR	17.5	18.6	.003	.39	.30	.03	.78
VGS	12.7	18.5	---	---	---	---	---
		λ_j =	0.281	0.065	0.016	0.008	0.00006

TABLE V

SELECTED PREDICTORS FOR THREE GROUPS OF CLOUD AMOUNT

X_i	$D_S^2-D_{S-1}^2$	$\chi^2_{.05}/P$	V_{1i}	V_{2i}
LAT	109.2	12.7	.594	.373
LNG	64.8	12.5	-.451	-.019
LTH	31.5	12.5	-.324	.579
VGS	16.8	12.3	.465	.270
SHR	21.8	12.2	.244	.528
U	13.1	11.9	-.252	-.415
SNH	7.9	11.7	---	---
		λ_j =	.235	.064

Predictors are listed in the first column (X_i) of Tables IV and V in the order of selection in the screening analysis. The statistical significance of each variable compared to the true minimum level of .05 can be made between ($D_S^2-D_{S-1}^2$) in the second column with $\chi^2_{.05}/P$ in the third. The columns subsequent to $\chi^2_{.05}/P$ give the values of the coefficient vectors for each of the two discriminant functions. The value of λ associated with each of the discriminant functions is listed below the column vectors.

The values of λ in Table IV show that most of the discrimination among the six groups was accomplished by the first discriminant function. The Euclidean distance in discriminant space, as used by Miller (1962), is weighted by the factor λ_j/λ_1 for each discriminant function. With this metric the first two functions contribute more than 90% to the total distance in this space. According to Miller there is no exact test available for judging the statistical significance of λ. On the basis of an approximate procedure he used the first two values in Table IV compare quite favorably with the two values of λ determined using three groups. Since λ measures the degree of separation in discriminating among the groups, the values obtained indicate a comparable or slightly better ability to discriminate among six groups than can be accomplished using only three.

Prior to discussing some of the details of the discriminant functions we shall examine the mean values of the selected predictors associated with the different groups of cloud amount. The group means illustrate some of the smoothing which occurs as a result of combining the observations into three classes of cloud amount. They are also helpful in understanding the different order of selection shown in Table V from that given in Table IV.

The mean values for the important synoptic parameters associated with each group are given in Fig. 15. The range of values included in one standard deviation of the group mean is also shown in this figure.

The geographical centroid for all the 1961 observations is near 33N, 153W. Observations which were clear or with only a few clouds had a mean value for the coordinates of 34.2N, 146.4W or very near the mean position of the center of the Pacific Anticyclone (Fig. B-1, Appendix B). The mean positions for the middle groups of cloud amount were located in the ridge of high pressure extending to the southwest of the Pacific Anticyclone. The groups with larger amounts of cloud cover have average position values slightly to the east of the mean location of the

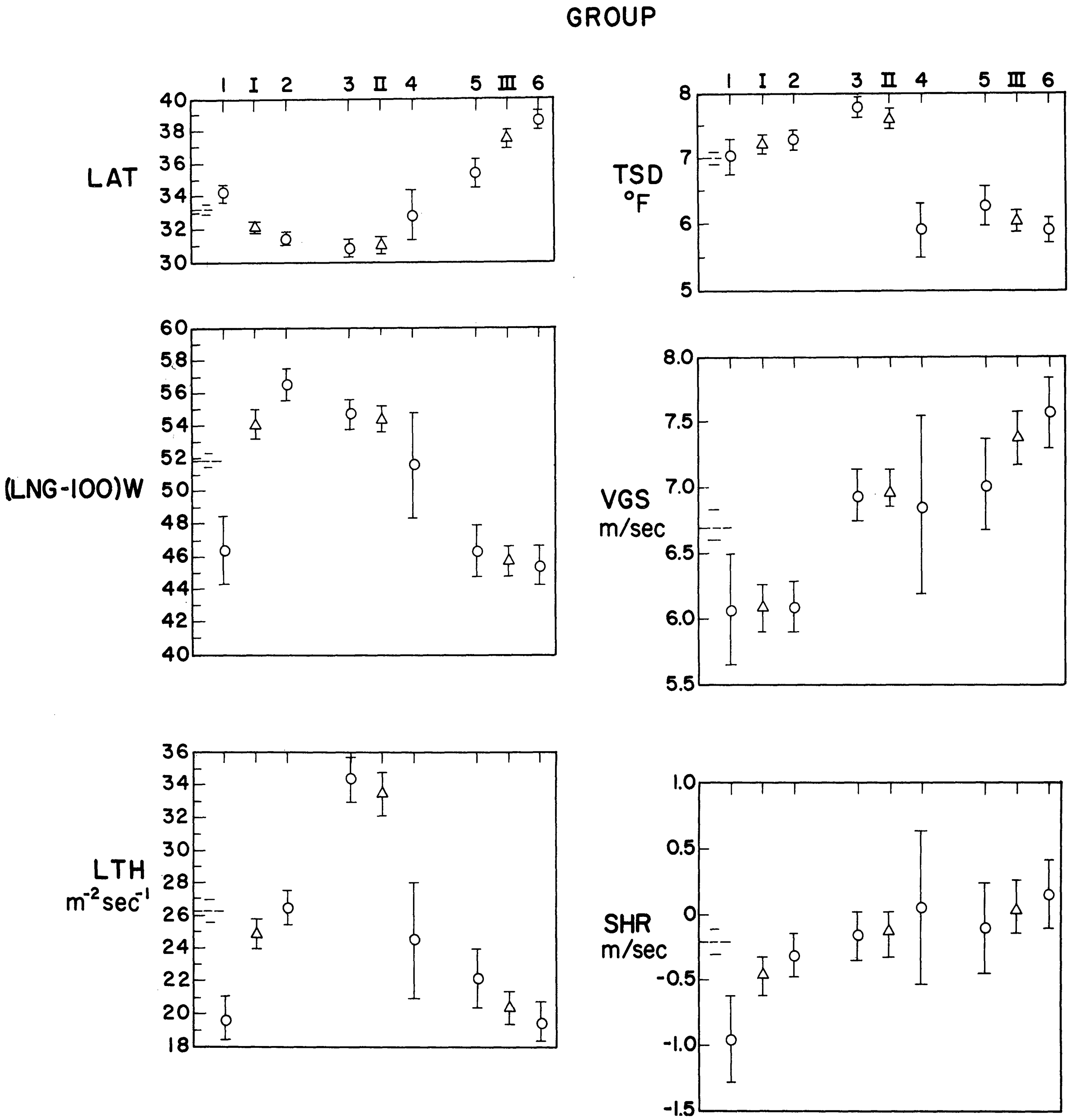

Fig. 15. Mean values of the important predictors and their standard deviations for cloud amount in three and six groups.

center of the anticyclone. The plot of these values in Fig. 15 shows only slight deviations of the six groups from the three groups.

The mean value of LTH for all the observations taken during the 1961 period was approximately 26 cal m^{-2} sec^{-1}. Four of the six groups have values less than the overall average. When there were no clouds present the average value of LTH was 20 cal m^{-2} sec^{-1}. This increased in a nearly linear manner to a maximum value of 34 cal m^{-2} sec^{-1} when the cloud amount was scattered. Successive increases in cloud amount were associated with decreasing values of LTH. Again, the change took place in a nearly linear fashion with increasing cloud amount.

The group mean values for TSD change in a manner quite similar to LTH with increasing cloud amount. The only deviation from a monotonic change around group 3 is presented by group 4. However, the group means within this category were computed from a relatively small number of observations. It is therefore quite likely that the mean value of TSD in this group is too low.

The overall average value of -0.2 $msec^{-1}$ for SHR indicates that, for this set of observations, the geostrophic wind at the surface is on the average slightly higher than it is at 850 mb. It averages nearly 1.0 $msec^{-1}$ larger for observations with no clouds present. At the opposite end of the cloud amount scale the 850-mb wind speed is slightly higher than the surface geostrophic wind speed.

The plots of group mean versus group number for each of the five variables just discussed show a loss of information as a result of combining the observations into three groups. However, the overall shape of the curve connecting these points would be maintained quite well by having only three groups. VGS shows a deviation from the general trend. The six group means for this parameter could be combined into three groups in a different manner than was done. The mean value of VGS for groups 1 and 2 was approximately 6.2 $msec^{-1}$. Groups 3, 4, and 5 had a mean value of VGS between 6.8 and 7.0 while group 6 had a mean value of 7.6. The cloud amount can therefore be distinguished by three regimes where the mean value of VGS remains essentially constant. The manner in which the cloud amounts were actually combined into three groups shows a linear increase in the mean value of VGS with increasing cloud amount. As a result it was selected as the second meteorological predictor. On the other hand, the reason why VGS was not selected as a significant predictor when discriminating among six groups of cloud amount can now be seen more clearly.

The principal assumption used in obtaining the values of the synoptic parameters is that of geostrophic motion at the surface. This, of course, involves an over estimate of the observed wind. Sheppard and Omar (1952) found the ratio of the observed to the geostrophic wind speeds at the surface varied from slightly less than 0.5 for low wind speeds to approximately 0.75 for high wind speeds. The observations were made over the islands of Wake, Johnston and Eniwetok in the Pacific. If we assume that these observations over small islands give a reasonable approximation to conditions over the open ocean the effect of the geostrophic assumption can be established.

Group means for VGS have shown that on the average low cloud amounts are associated with low wind speeds and vice versa. The difference in the surface wind speed, between the small and large amounts of cloud cover, using the geostrophic approximation, is then a conservative estimate of the difference which exists for the observed wind. The effect of the geostrophic assumption on the computation of values for LTH is not so straightforward. The use of the observed wind would most likely show an increase in the difference between the mean values associated with clear skies and scattered cloud amounts. Group mean values of SHR should show less differences among them along with a translation along the one axis toward increased positive values.

The discussion up to now has been concerned exclusively with results obtained using the observed magnitude of the synoptic parameters. The quasi-stationary condition of the Pacific Anticylone results in favored regions for the occurrence of different amounts of cloud cover. The geographical coordinates of latitude and longitude are therefore two of the most important predictors in discriminating among groups of cloud amount. If the same methods of analysis are to be applied to the cloud patterns found in the migratory anticyclones, they must necessarily yield results which are independent of the specific latitude and longitude. Such migratory systems could use a relative coordinate system with the origin at the center of the anticyclone.

An effort was made to determine the effects of latitude and longitude on the mean conditions for each group of the cloud amount. The meteorological predictors were made independent of the geographical coordinates by using the deviation from climatology at the location of the observation. The group means, as a deviation from climatology, for the three meteorological parameters found to be most significant in the previous analysis are shown in Fig. 16. The overall mean deviation from climatology was subtracted from the group means in order to make each group mean a true deviation.

The group means for LTH and TSD, shown in Fig. 16, change among groups in a manner almost identical to the changes in the group means shown in Fig. 15. The only real difference was in the relative position of the group 2 mean for TSD. The group means for VGS, as a deviation from climatology, are somewhat different in the relative position from those made up of the magnitudes of VGS. Groups 1 and 2 are associated with wind speeds less than the climatological value. The mean wind speeds associated with groups 3 and 4 are very near the climatological value at the observation point. On the average, the wind speed is greater than the climatological value at the observation location when either groups 5 or 6 are present.

These values as deviations from climatology have shown some changes from the group means obtained as magnitude of the meteorological predictors. However, the results obtained by using the magnitudes of the quantities along with latitude and longitude have served to downgrade the importance of those meteorological parameters which would be selected if latitude and longitude were not used. Such variables as the absolute

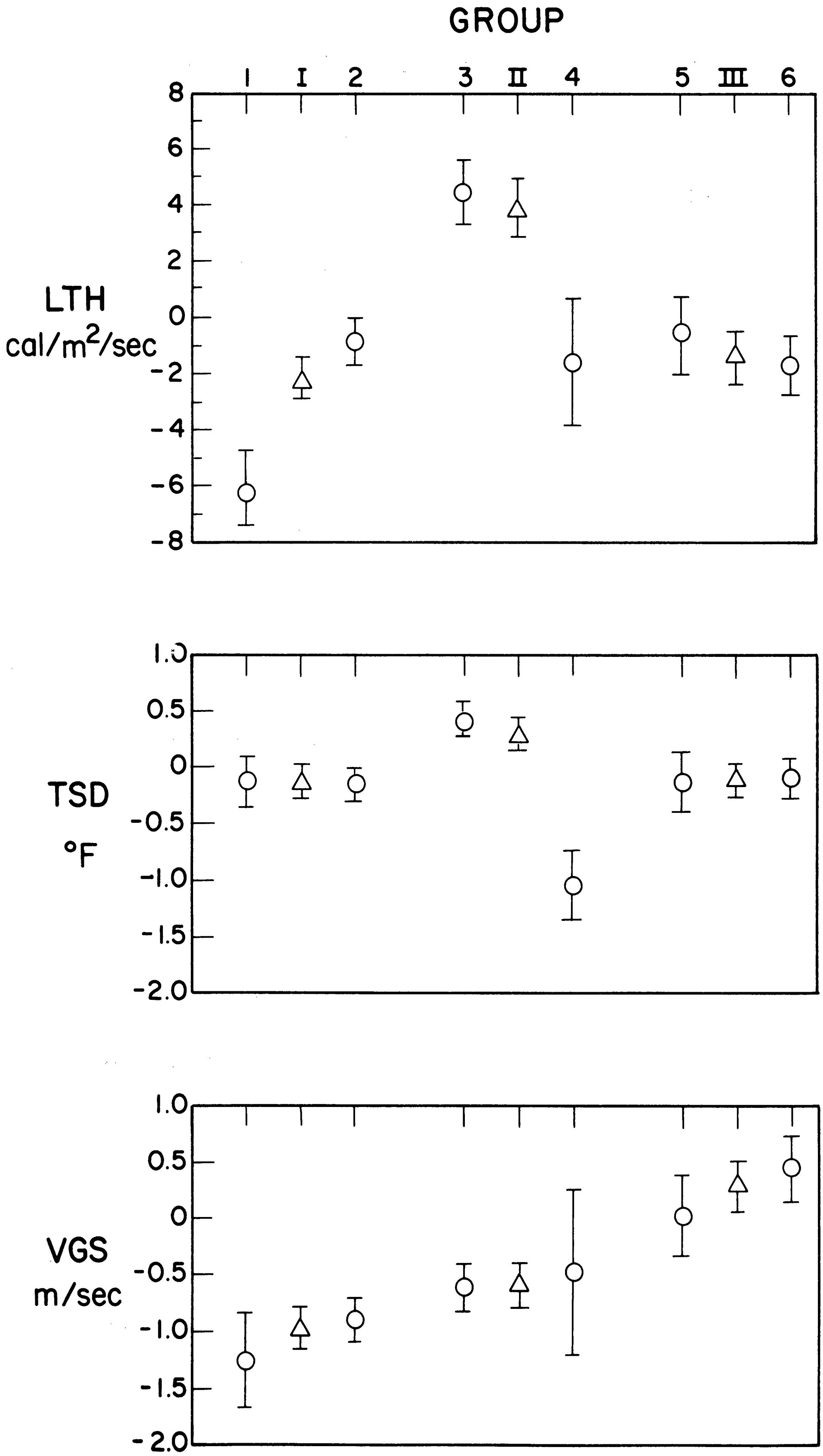

Fig. 16. Group means and their standard deviations, as departures from climatology, associated with different groups of cloud amount.

vorticity and the U-component of the surface wind are highly dependent on the latitude. The V-component of the surface wind is very highly correlated with longitude. In the absence of latitude and longitude as predictors one or more of these meteorological variables would be selected in the screening analysis. The results obtained in this manner would be very difficult to interpret.

5.2.2 Values of the Discriminant Functions

Normalizing the values of the synoptic variables prior to the screening analysis enables us to determine the importance of a given predictor within each discriminant function. In the analysis of six groups, latitude and longitude provide the main contribution in the first and most important of these functions (V_{1i} in Table IV). The two predictors determine a line through the geographical region connecting the predominant zones of low and high cloud amounts. The major zone of low cloud amount was located in the southwest quadrant while large amounts of cloud cover were found most often percentagewise in the northeast quadrant. The only other predictor contributing a significant amount to this first function is TSD.

The value of the second discriminant function (V_{2i} in Table IV) is determined largely by the value of LTH. Its coefficient is twice as large as that for any of the other predictors. LAT and SHR are the other two predictors for which the coefficient allows a significant contribution in determining the magnitude of the second discriminant function. The proximity of some of the group means for LTH, SHR and LAT to the overall mean (Fig. 15) allows for a significant contribution to the average value of the function by predictors having relatively small coefficients. In general, the interaction of the predictors within the second discriminant function is much more complex than it was in the first. Considering the greater importance of the first discriminant function over the second one could surmise that LAT and LNG are the important predictors for the two extremes of cloud amount. In the middle groups, where the differences in these two predictors from one group to the other are less great, the predictor TSD exerts a strong influence in the discrimination.

The degree of importance for the same predictors was changed somewhat when the observations were combined into three groups. One of the desirable features achieved by the combination was to reduce the importance of the geographical location relative to the meteorological predictors. This can be seen by comparing the values of the coefficients in the first discriminant function when using six groups (V_{1i} in Table IV) with the relative values for the same predictors when using three groups (V_{1i} in Table V). None of the predictors in the first function with three groups is weighted so heavily as to exclude some of the others. This more even distribution in the magnitude of the coefficients shows that there has been a considerable amount of smoothing achieved by combining the observations into three groups. Some of this smoothing has already been shown by the group means in Fig. 15.

The mean values of the two important discriminant functions for six groups are plotted in Fig. 17. This shows a composite of the mean values for all groups and the 50% contour ellipses assuming bivariate normality in the modified discriminant space Y_1 and $(\lambda_2/\lambda_1)^{1/2}Y_2$. The modified discriminant space shows the amount of discrimination achieved since the Euclidean distance is weighted by the factor (λ_j/λ_1). (See Miller, 1962 for further details.) The mean and 50% contour ellipse for the discriminant functions using three groups are shown in Fig. 18.

The principal feature in each of the figures is that there has been a definite separation in the vector means of the discriminant functions, but the large dispersion about the vector means reduces the amount of discrimination achieved. As a result of the latter factor it is practically impossible to specify the occurrence of group 4 (Fig. 17).

5.2.3 Accuracy of Specification and Comparison With Climatology

The importance of a given predictor in discriminating among various groups of a cloud parameter can be determined, at least qualitatively, by examining the results obtained in different steps of the statistical analysis. The final test of a statistical prediction scheme is nevertheless the ability to predict correctly using independent data. The multiple-discriminant analysis technique was used to predict the cloud amount group using the selected predictors. This was done with both the dependent sample (1961 observations) and the independent sample (1962 observations). The results for the dependent sample using three groups of cloud amount are

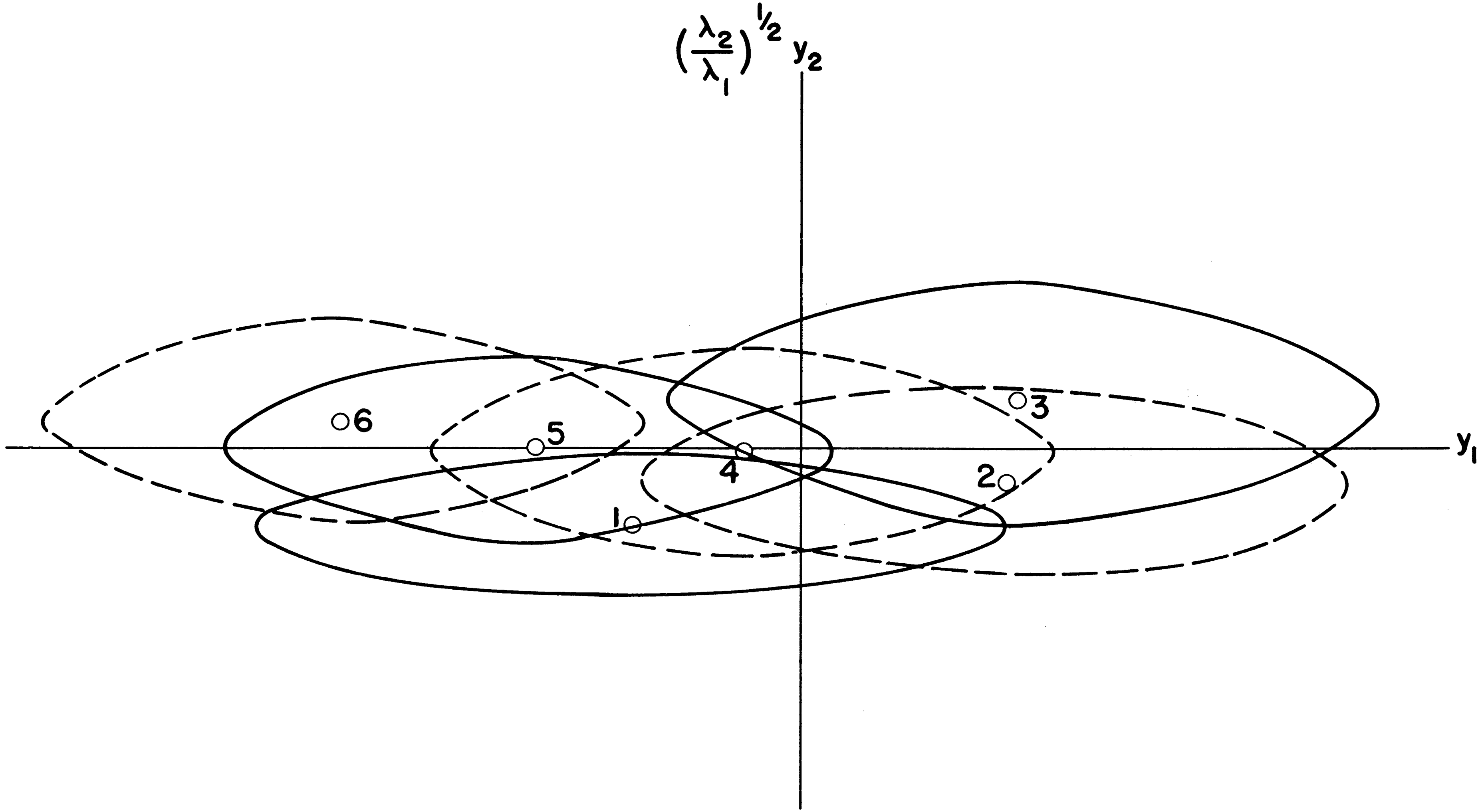

Fig. 17. Mean and 50% contour ellipse of the first two discriminant functions for each of the six groups of cloud amount.

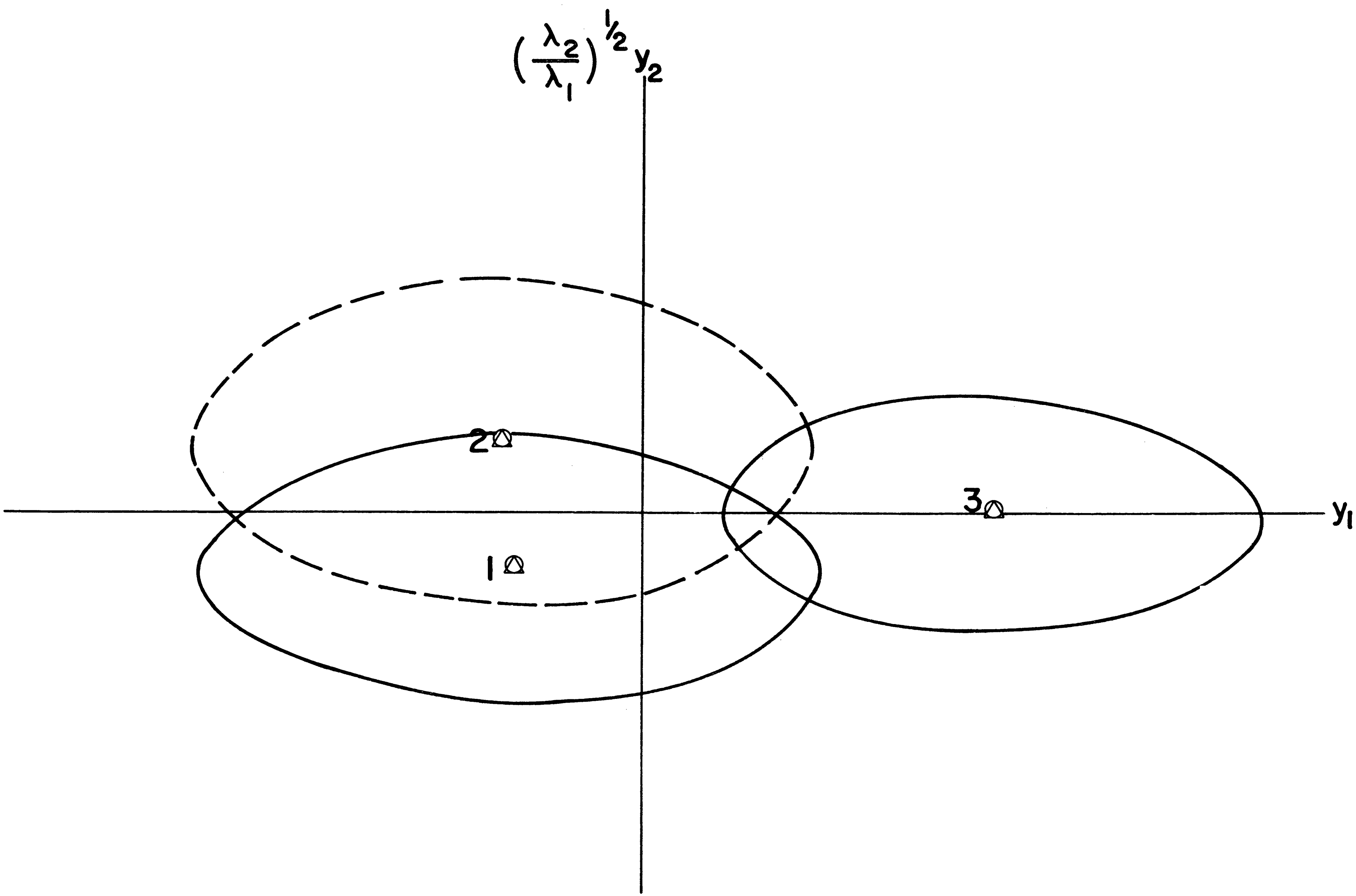

Fig. 18. Mean and 50% contour ellipse of the two discriminant functions for each of the three groups of cloud amount.

shown in Table VI. The same type of results for the independent sample are shown in Table VII. A summary of the results obtained using six groups of cloud amount are shown in Table VIII for the dependent sample and Table IX for the independent sample. In predicting the occurrence of a group, it is sometimes the case that two or more groups show the same probability of occurrence. The total number of occurrences in the sample in which this was also the maximum probability were divided evenly among the affected groups.

TABLE VI

RESULTS FOR SPECIFICATION OF CLOUD AMOUNT IN THREE GROUPS
(Dependent Sample)

Observed	Specified 1	2	3	Total
1	217	71	68	356
2	105	112	61	278
3	47	25	173	245
Total	369	208	302	879

No. Correct = 502, Skill Score = 0.28

TABLE VII

RESULTS FOR SPECIFICATION OF CLOUD AMOUNT IN THREE GROUPS
(Independent Sample)

Observed	Specified 1	2	3	Total
1	197	85	90	272
2	117	77	132	326
3	39	20	105	164
Total	353	182	327	862

No. Correct = 279, Skill Score = 0.05

TABLE VIII

RESULTS FOR SPECIFICATION OF CLOUD AMOUNT IN SIX GROUPS
(Dependent Sample)

Observed	Specified						
	1	2	3	4	5	6	Total
1	9	39	14	0	3	20	85
2	3	174	59	0	5	30	271
3	4	88	125	0	6	29	252
4	2	9	6	0	4	5	26
5	6	19	14	0	12	35	86
6	7	21	21	0	8	102	159
Total	31	350	239	0	38	221	879

No. Correct = 422, Skill Score = 0.25

TABLE IX

RESULTS FOR SPECIFICATION OF CLOUD AMOUNT IN SIX GROUPS
(Independent Sample)

Observed	Specified						
	1	2	3	4	5	6	Total
1	6	24	8	0	8	20	66
2	9	160	91	0	7	39	306
3	3	83	108	0	5	57	256
4	2	19	12	0	6	31	70
5	4	14	9	0	3	54	84
6	5	20	19	0	2	34	80
Total	29	320	247	0	31	235	862

No. Correct = 311, Skill Score = 0.07

The skill score listed at the bottom of each table is determined from

$$\text{Skill Score} = \frac{R-C}{T-C}$$

where R is the number of observations specified correctly, C is the climatological frequency as determined by continuously specifying the group with the largest number of observations in the dependent sample, and T is the total number of observations in the dependent or independent sample.

There were 57% of the observations specified correctly when using the dependent sample in three groups. When the independent sample was used there were 44% specified correctly. The results were 48% and 36% correctly specified for six groups in the dependent and independent sample, respectively. Unquestionably, the percentages indicate results significantly better than random selection. The improvement over climatology is not nearly so definite in all cases. The skill score does however show a positive value in all cases. The fact that no observations were specified in group 4 (Tables VIII and IX) precludes the use of any further valid statistical tests on these contingency tables.

5.2.4 Summary of Results for Cloud Amount

The group means of the meteorological variables associated with different cloud amounts present a description of the mean conditions such as the following: clear skies are associated with the lowest wind speeds. The air-dewpoint temperature difference is very near the overall mean so that the driest conditions in the surface layers do not necessarily occur with clear skies. A change from clear to conditions with less than scattered clouds results in a slightly larger spread between the air and dewpoint temperatures. Cloud amounts in the range from scattered through broken have a nearly constant mean wind speed of approximately 7 $msec^{-1}$. (This is the speed usually given for a change of sea conditions from smooth to rough.) The amount of cloud cover occurring within this range is determined largely by the relative amount of moisture in the air, i.e., TSD. An increase in cloud cover to mostly overcast skies has an associated increase in the mean value of VGS as well as an increase in the relative amount of moisture in the surface layers, i.e., a decrease in the average value of TSD. The amount of cloud cover present is then related to the three temperatures used as well as the surface wind speed. One parameter which summarizes this relationship best is LTH which was the first meteorological variable selected.

It was possible to achieve a relatively large distance between the vector means of the discriminant functions. The large spread of the points about the vector means greatly decreased the amount of discrimination among groups of cloud amount.

Nearly all the evidence indicates that the amount of cloud cover should be specified in the six groups rather than the three of mostly clear, partly cloudy and cloudy. It would appear that with a more objective scheme of determining the cloud cover at least 10 groups could be used.

The ability to specify only 57% of the dependent sample correctly indicates that either the minimum value for statistical significance was placed too high or that all of the significant predictors were not included. The latter is more likely and the inclusion of more detailed upper air information as possible predictors should yield a significant improvement in the results.

5.3 CUMULUS CELL SIZE IN THREE AND FOUR GROUPS

5.3.1 Preliminary Remarks

First results of the screening analysis for predictor selection in discriminating among groups of cell size showed the mean solar time THR to be very important. LNG was also selected but LAT was missing. The frequency distributions given in Fig. 11 show that cell size is definitely a function of longitude and should also be related to latitude to a significant degree. Further analysis proved that THR was related to LAT and LNG when used in conjunction with cell size.

The manner in which this relationship exists is as follows: The cell size is a function of LAT and LNG to a significant degree. The minimum nadir angle, and therefore the region observed by the TIROS III camera progressed northward during the period from August 15 to September 5, 1961. The precession of the orbit resulted in the average time of the observations becoming earlier on each succeeding day. The three combined to make the mean solar time for the observations of cell size a function of latitude and longitude. The arguments presented above were substantiated by including the identification number of the observation in the list of possible predictors. Observations were numbered consecutively according to the time the satellite picture was taken in the three week period. The screening analysis selected the identification number of the observation as the most important predictor in discriminating among the three groups of cell sizes by a wide margin over any of the other 21 variables.

It was therefore quite conclusively demonstrated that, because of the behavior of the TIROS satellite during the period of the observations, it is not possible to determine whether the size of the cumulus cells is a function of the time of the day. The mean solar time was thus discarded from any further consideration as a possible predictor for discriminating among groups of cell size.

5.3.2 Selection of Predictors

After the elimination of the mean solar time, the observations were screened twice for selecting predictors from among the 20 remaining synoptic variables. In the first of these only the three specific size ranges of small, medium, and large were used. For the second screening analysis the "catch-all" category of mixed cell sizes was added as a fourth group. The number of observations within each of these groups were:

small	148 observations
medium	141 observations
large	130 observations
mixed	149 observations

The total number of observations in the three groups containing specific cell sizes was 419. Earlier experience has indicated that in order to discriminate among more than two groups, with the quality of data used, the minimum total sample size should be on the order of 500 observations. However, if we assume that an increase in the number of observations would show the same distribution of the synoptic variables within the groups of cell size, it is quite simple to estimate the effect of this increased number on the factor of statistical significance. When the mixed cell size observations are included as a fourth group the total number is increased to 568, which is above the desired minimum number.

The first five variables selected by these two separate analyses of the cell size were the same, although the order of selection was different. Some of the selections were marginal with regard to the prescribed statistical significance. However, it is not unreasonable to expect all of them to achieve full statistical significance if the number of observations was increased by a substantial amount.

In the first screening analysis, which used only the cell size in the three specific groups of small, medium, and large, the five predictors in the order of selection are listed in Table X. This table also gives the value of $(D^2_S - D^2_{S-1})$ obtained along with the χ^2 value needed for statistical significance at the true level of .05 for each predictor. The last two columns give the values of the coefficient vectors for each of the two discriminant functions. The value of λ for each of the discriminant functions is listed as the last number in the column vector of coefficients. Table XI presents the same type of information as given in Table X, but is valid for the analysis of cell size in four groups.

TABLE X

SELECTED PREDICTORS FOR CELL SIZE IN THREE GROUPS

X_i	$(D_S^2 - D_{S-1}^2)$	$\chi^2_{.05}/P$	V_{1i}	V_{2i}
LNG	29.5	12.6	-.449	.589
VSHR	29.4	12.5	.330	-.180
ZA	19.1	12.3	.375	.443
VGS	17.9	12.2	.609	.230
SHR	20.2	11.9	.422	.609
SNH	6.1	11.7	---	---
		λ_j =	.258	.030

TABLE XI

SELECTED PREDICTORS FOR CELL SIZE IN FOUR GROUPS

X_i	$(D_S^2 - D_{S-1}^2)$	$\chi^2_{.05}/P$	V_{1i}	V_{2i}	V_{3i}
ZA	31.7	14.8	.383	.521	-.212
VGS	33.6	14.6	.610	.299	-.445
LNG	28.6	14.4	-.509	.641	-.310
SHR	13.4	14.3	.350	.384	.740
VSHR	11.2	14.1	.316	-.286	.337
DTN	6.9	13.9	---	---	---
		λ_j =	.185	.026	.006

An examination of Tables X and XI reveals that, although five synoptic variables were selected, they pertain to only two specific parameters, i.e., location and wind. The only synoptic variable pertaining directly to the wind field not selected was the horizontal divergence. It is particularly noteworthy to point out that latitude as an independent variable was also not selected. However, the latitude is definitely present in the form of the absolute vorticity (ZA). This was the third predictor selected in the screening analysis of the three specific cell size groups, whereas, it was the first predictor selected when the group of mixed cell size was included as a fourth group in the screening analysis.

The mean values of each of the selected predictors occurring with each of the four groups of cell size are shown in Fig. 19. The mean value of the latitude for each of the four groups is also included in this figure to aid in the interpretation of the group means for the meteorological predictors.

The group means for the geographical locations show that only the one containing observations of small cell size has any strong tendency for a preferred location within the Pacific Anticyclone. The mean location of 29.8N, 158.5W for this group is southwest of the mean position for the center of the Pacific Anticyclone (Fig. B-1, Appendix B). The frequency distributions of observations of cell size (Fig. 11) shows that approximately 60% of those classed as small were located in the southwest. The group containing observations of medium cell size has mean geographical coordinates of 30.8N, 150.5W showing no tendency for any preferred location. This can also be seen in Fig. 11. The mean location of 34.1N, 149.8W for the groups with large cell size is very near the center of the region used in this study and would appear to indicate a uniform distribution of these observations. Figure 11 however, shows an equally large number of occurrences in the NW and SE quadrants. A much smaller number of observations was obtained from the SW and NE quadrants. The observa-

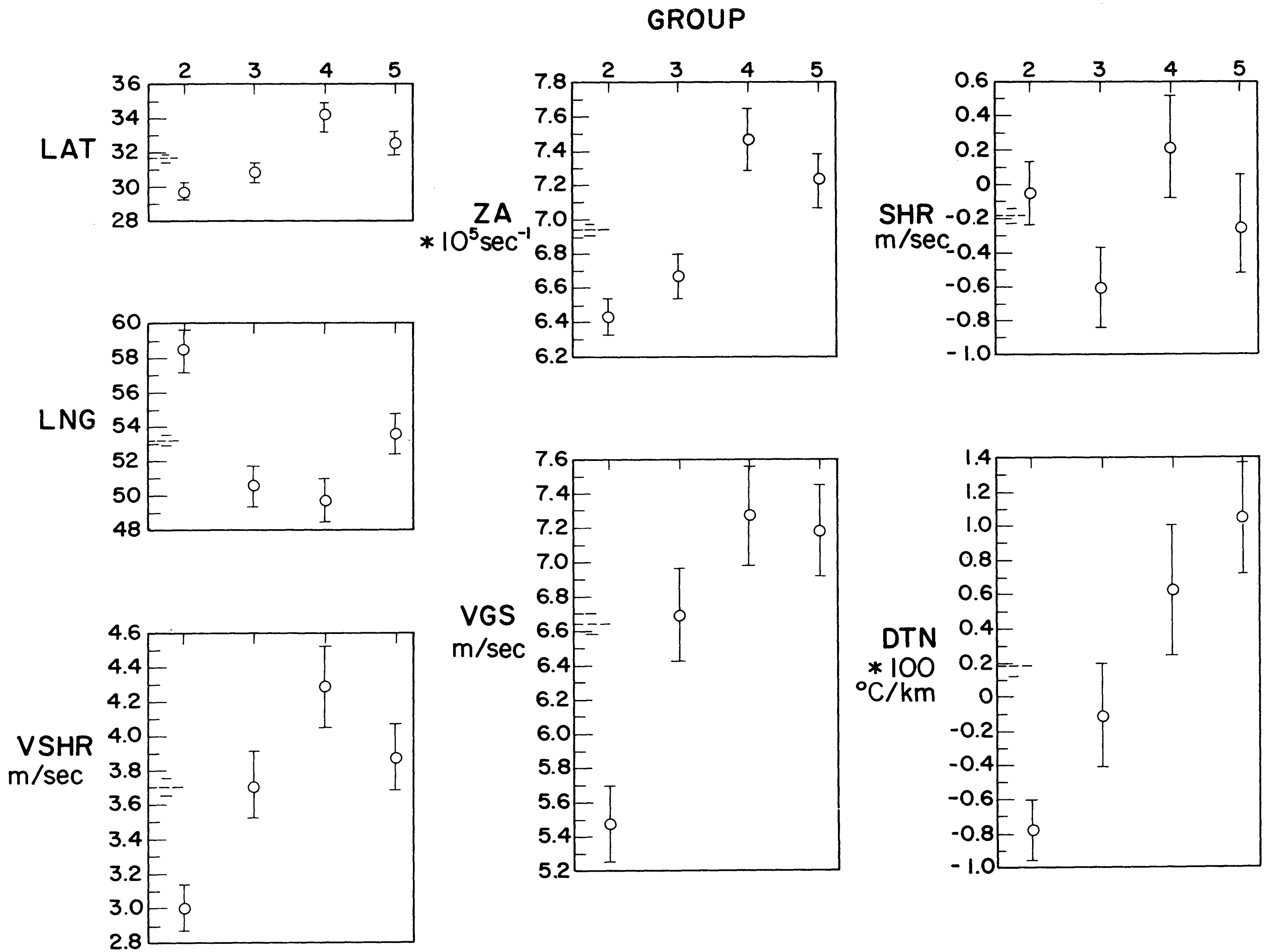

Fig. 19. Mean values and their standard deviations of the important predictors for cell size in four groups.

tions of mixed cell size show only a slight preference for the SW quadrant with a mean location of 32.5N, 156.7W.

The contribution of the latitude to the absolute vorticity is quite evident when one compares the curve connecting the mean values of each with increasing group number. When the effects of latitude are taken out, the mean value of the realtive vorticity showed a linear increase with increasing group number. For small cell size the mean value of the relative vorticity was approximately -0.8×10^{-5} sec^{-1}. The value increased to approximately -0.5×10^{-5} sec^{-1} for the group with mixed cell size.

The selection of both the synoptic variables pertaining to the difference in the wind field between the 850-mb level and the surface serves to point out the importance of the vertical wind shear in association with various groups of cumulus cell size. The magnitude of the vector difference in wind speed between the 850-mb level and the surface (VSHR) was the first meteorological predictor selected in discriminating among three groups of specific cell size. When the mixed cell size was included as a fourth group, VSHR was the fourth meteorological predictor selected. At least part of the reason for this order of selection can be seen in the value of the group means for VSHR (Fig. 19). When only the three specific cell size groups were used the mean value of VSHR increased in a nearly linear manner from 3.0 $msec^{-1}$ for small to 4.3 $msec^{-1}$ for the group with large cell size. The mean value of VSHR occurring with the group of mixed was 3.9 $msec^{-1}$.

The scalar difference in wind speed between the 850-mb level and the surface (SHR), was selected as the fifth predictor in discriminating among the three groups. However, it was selected fourth, ahead of VSHR, when the group of mixed was included. The value of the group means for SHR do not show the distinct differences among groups that the other variables do. The low order of selection for SHR in each of the two analyses also makes the interpretation more difficult because of its relationship to the predictors previously selected.

The sixth predictor selected when discriminating among the four groups of cell size was the thermal gradient normal to the surface wind (DTN). Experience has shown that for this set of data the value of $(D_S^2-D_{S-1}^2)$ levels off somewhere between three and four. There is a strong possibility that a weak signal above the noise level is being given by the variable DTN. It is suggested that DTN merely completes the picture of the extremely large dependence which the cell size has on nearly all aspects of the wind field between the surface and at least as high as the 850-mb level.

One of the more surprising aspects resulting from the analysis of cell size is the complete lack of dependence on the vertical stability parameter. The meteorological variable which could give some estimate of the depth of the convective layer is the deviation of the observed height of the 850-mb level from that computed for an adiabatic atmosphere (Z85). In particular, if the larger cell sizes result from a horizontal spreading of the clouds below a subsidence inversion, Z85 could be expected to be selected as a significant predictor. The value for the matrix trace of Z85 was the lowest of any of the 20 possible predictors. A further illustration of the complete lack of importance of Z85 in discriminating among cell size is given by the group means. The largest difference between any of the four group means was less than 1 m.

5.3.3 Specification in Four Groups of Cell Size

The mean values of the discriminant functions for each of the four groups together with the 50% contour ellipse are plotted in Fig. 20. The distances between the group means for the three specific sizes were quite large and even though the dispersion is high the discrimination should be relatively good. The location of the mean value of the group with mixed sizes together with the large dispersion greatly decreases the amount of discrimination obtained.

The results obtained when the cell size groups were specified in the dependent sample are shown in Table XII. The same information for the independent sample is given in Table XIII. Since the same predictors were selected in both cases only the four groups were tested for specifying the classes. Figure 20 indicates that the results for the specifications would be much better if the fourth group was excluded.

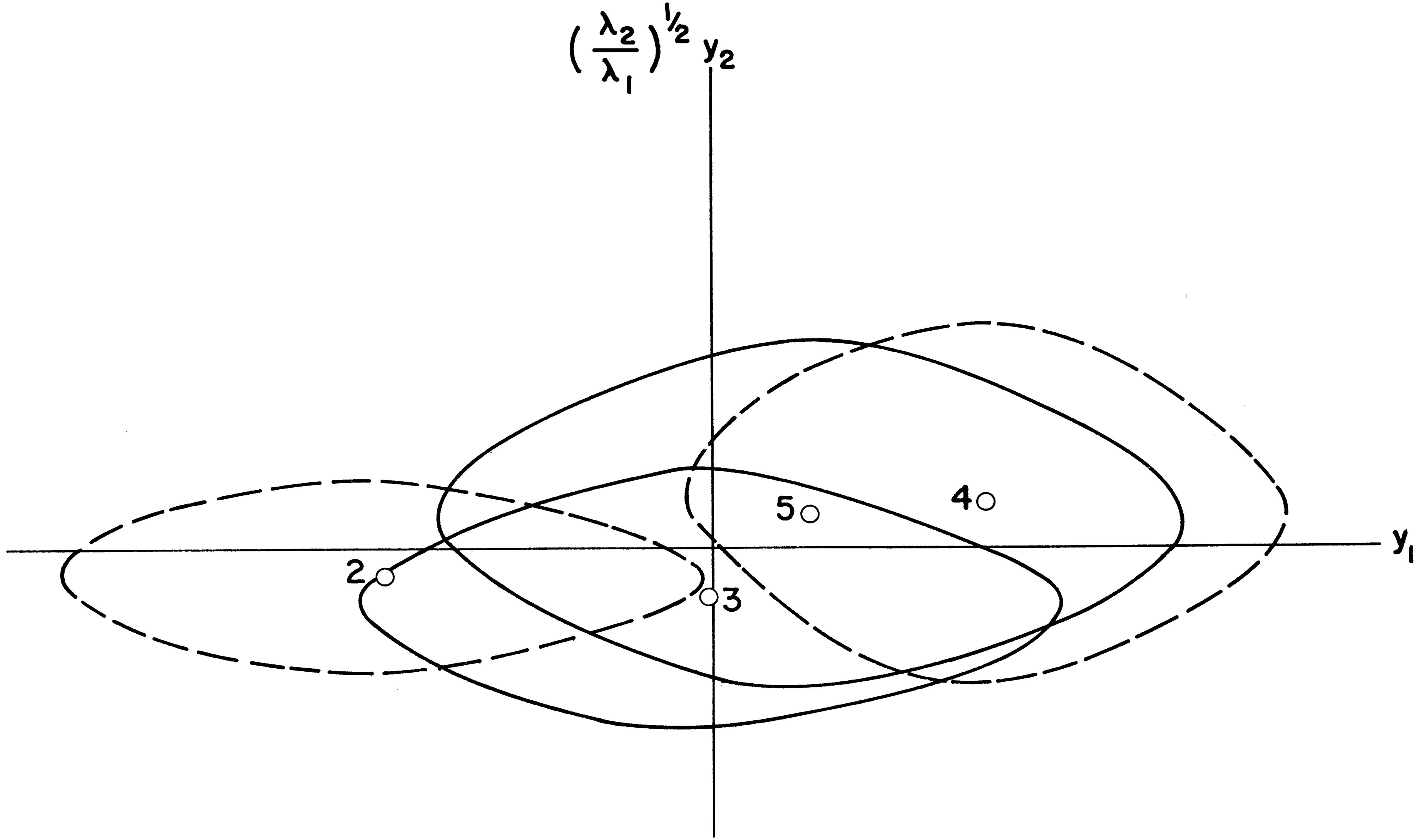

Fig. 20. Mean and 50% contour ellipse of the first two discriminant functions for each of the four groups of cell size.

TABLE XII

RESULTS FOR THE SPECIFICATION OF CELL SIZE IN FOUR GROUPS
(Dependent Sample)

Observed	Specified 2	3	4	5	Total
2	85	22	22	19	148
3	44	46	28	23	141
4	13	28	66	23	130
5	38	26	40	45	149
Total	180	122	156	110	568

No. Correct = 242, Skill Score = 0.22

TABLE XIII

RESULTS FOR THE SPECIFICATION OF CELL SIZE IN FOUR GROUPS
(Independent Sample)

Observed	Specified 2	3	4	5	Total
2	78	56	53	34	221
3	29	34	48	38	149
4	8	16	15	23	62
5	56	43	32	41	172
Total	171	151	148	134	604

No. Correct = 168, Skill Score = 0.04

There were 43% of the observations specified correctly in the dependent sample but only 27% correct with the independent data. The bias toward the smaller cell sizes in the 1962 period, indicated in Section 3.3, shows more clearly in Table XIII. The large size was specified more than twice as often as it was observed in the 1962 period. The increase in the number of times group 4 was specified but 2 or 3 was observed in the independent sample over that shown in Table XII accounts for a significant portion of the difference in the number correct.

5.3.4 Summary

The screening analysis selected the same five predictors when discriminating among the cell size in three and four groups. These constituted the location of the observation and information about the motion field.

The scalar and vector difference in the wind between the 850-mb level and the surface were both selected in the screening analysis. Group mean values of the vector difference increased in a nearly linear manner with increasing cell size.

Discrimination among the three groups of specific cell size was very good. Figure 20 and Table XII both show the deleterious effects of specifying a group classed as mixed cell size. The indications are that a classification scheme based on the predominant cell size and elimination of the "mixed" group would have been better than the one used.

The climatological frequency for the dependent sample was only about 26%. The discriminant analysis showed a significant improvement over this figure, and much better than that attained when discriminating among groups of cloud amount. The independent sample contained a bias toward the smaller cell sizes. The ability to specify the cell sizes for such a sample can therefore not be determined.

5.4 OCCURRENCE AND SIZE OF CLOUD BANDS

5.4.1 Preliminary Remarks

There were 146 cases during the 1961 period in which some form of banding data was apparent in the cloud pattern. The total includes 78 observations which were classed as small, i.e., a spacing of less than about 40 km, with the remaining 68 observations classed as large or with a spacing greater than approximately 40 km. In order to obtain the minimum sample size of 500 observations considered necessary to discriminate among more than two groups would entail having at least 350 observations in the one with no banding. Even though this number of observations was available it was more important to consider another consequence of using an unequal distribution of observations in the analysis.

The effect of a large disparity in the number of observations within different groups with the method of discriminant analysis is that the group having the largest number of observations is weighted much heavier than those with fewer observations. It is more often the case in meteorology that the rare event is the most important with regard to prediction. Such is the case when considering the occurrences of cloud bands in different sizes which appear as rare events when compared to the number of occurrences of clouds with no apparent banding. During the 1961 period small bands were apparent in less than 9% of the observations whereas large bands occurred in only about 8%. Miller (1962) suggests that in such a case one should make the group frequencies more nearly equal when screening the predictors so as to emphasize the prediction of the important groups.

The only way to meet the two requirements of more than 500 observations in the total and without large disparities in the number within any one group was to combine the observations for the two time periods into one set. This yielded 384 cases of banding. Of this total there were 233 cases of small size bands and 151 cases in which the bands were classed as large. It was decided that the total for the three groups would be 600. The 216 observations used, in which there was no banding apparent, were selected as a random sample from the combined set in which the cloud amount was between groups 2 and 5, inclusive.

In the initial screening analysis for predictor selection, latitude, longitude and mean solar time were among those selected as statistically significant. When the mean solar time was selected as a predictor for discriminating among specific cell size categories it was found that it was simply a substitute for latitude. The orbital characteristics of TIROS III together with the principal geographical location of the various cell sizes combined to make the mean solar time a function of latitude. The manner in which the mean solar time influences the categories of banding is somewhat more subtle. The change in the frequency distribution of observations of band size from the 1961 to the 1962 period was discussed in Section 3.3. Table II showed that the largest change took place in the number of occurrences as well as the location of the observations of small band size. The result of the change is to weight the mean solar time for this group toward that which occurred during the 1962 period. On the average, the observations during this period were taken about 1 hr earlier in the solar day than those in 1961. The change in frequency of occurrence of banding from one year to the next is in all probability the result of changes in the meteorological conditions and not due to the slight difference in time of the observations. Therefore, it was concluded that the mean solar time appears as a significant predictor in discriminating among groups of cloud banding as a result of an inherent bias occurring in the set of observations. The mean solar time was thus discarded from any further consideration as a predictor for cloud banding.

5.4.2 Predictors Selected in the Screening Analysis

When the combined set of observations of banding was again submitted to a screening analysis, there were four variables selected and statistically significant, at the .05 level. These variables, in the order of selection were longitude (LNG), deviation of computed 850-mb height from the observed (Z85), sensible heat transfer (SNH), and latitude (LAT). The fifth predictor selected was the magnitude of the vector difference in wind between 850 mb and the surface. The value of $(D_S^2 - D_{S-1}^2)$ for this parameter was 8.6 compared to the 11.9 needed in order to be considered statistically significant at the true level of .05. When the screening analysis was allowed to proceed with the selection beyond the fifth predictor the value of $(D_S^2-D_{S-1}^2)$ dropped to about 4.5. This value, together with the number of observations used, suggests it is probably not far above the noise level. Pertinent information relative to the predictors selected is given in Table XIV. A comparison of the values of $(D_S^2-D_{S-1}^2)$ shown with those given in the previous tables of this type (Tables IV, V and X) demonstrates that the size of the bands have not achieved the same degree of success in identifying statistically significant predictors as was experienced using cloud amount or cell size.

TABLE XIV

SELECTED PREDICTORS FOR BAND SIZE IN THREE GROUPS

X_i	1961 and 1962		1961		1962	
	$(D_S^2-D_{S-1}^2)$	$\chi^2_{.05}/P$	V_{1i}	V_{2i}	V_{1i}	V_{2i}
LNG	26.4	12.6	-.614	.552	-.690	-.030
Z85	18.1	12.5	-.407	.135	.321	-.525
SNH	11.1	12.3	-.371	-.709	.173	.788
LAT	13.2	12.2	-.072	.132	.605	.206
VSHR	8.6	11.9	.561	.398	-.159	.243
		λ =	.029	.016	.201	.030

Part of the reason for the lack of ability to discriminate among the three groups of cloud bands is evident in the mean values of the selected predictors associated with the different groups shown in Fig. 21. Values associated with the groups having no banding (group 1) were determined from the sample of 216 observations used in the screening analysis. SNH is the only variable which shows a definite distinction among the mean

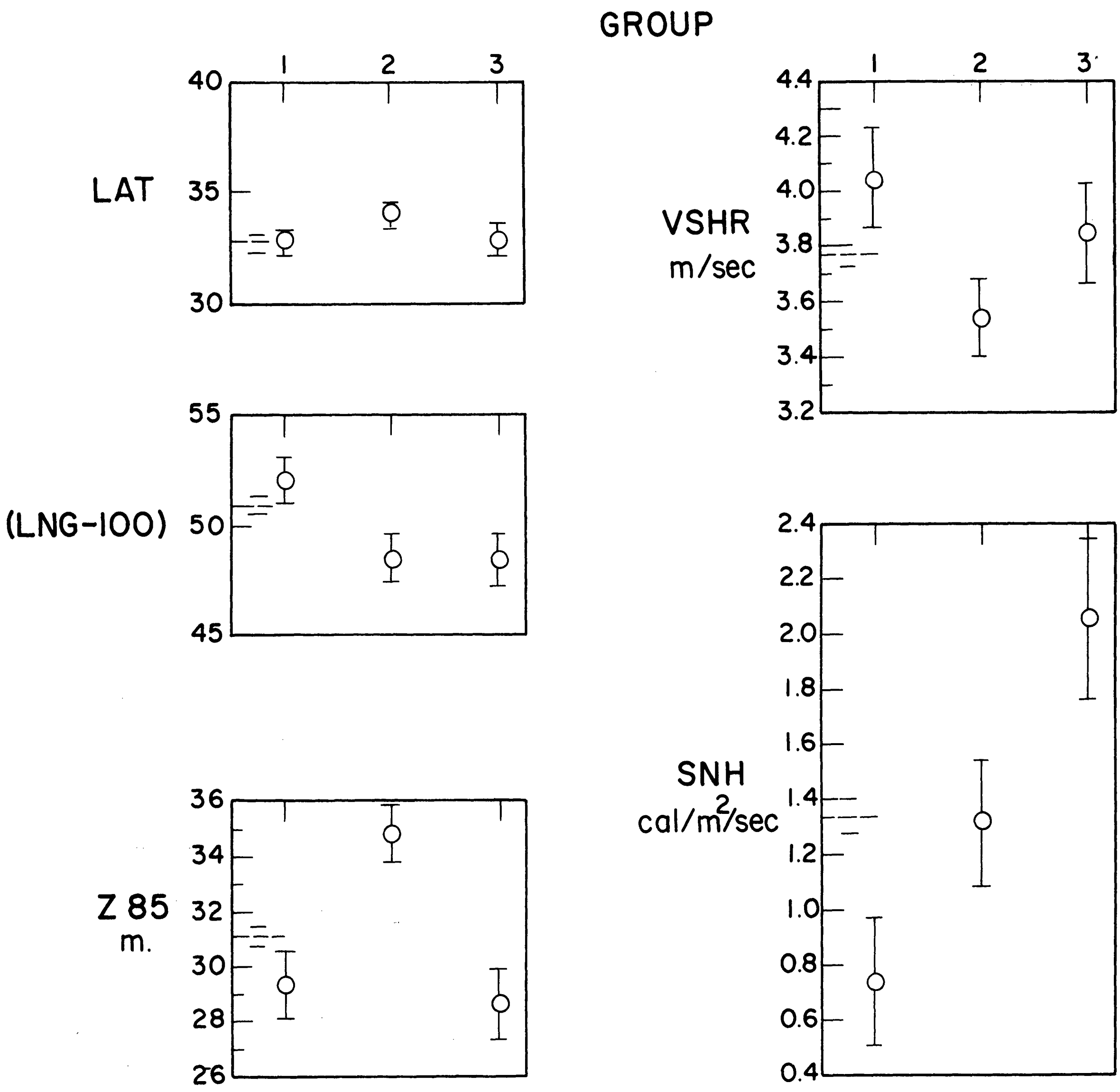

Fig. 21. Mean values and their standard deviations of the important predictors for the three groups of banding.

conditions for the three groups. The fact that it was not selected earlier than third indicates a relatively large variance within the groups compared to the variance among the groups. The first predictor is selected solely on the largest value of the ratio of the two quantities. The ratio for SNH was about 50% less than the ratio for the first predictor selected, i.e., LNG. The group means for the predictors other than SNH have one value different from the other two. The particular groups in which this occurs is not the same for each of the predictors. On the basis of the group means the discrimination would appear to be between one group and the other two groups combined.

The values of the group means for the first meteorological predictor selected, i.e., Z85, show that the discrimination was primarily between the small size bands (group 2) and the other two groups combined. It also indicates that the layer between the surface and 850 mb, when considered as a single entity, is more stable when small bands are present. In terms of the mean temperature in the layer, the difference is slightly greater than 1°C warmer for the cases in which small size bands occur. The computations for the height of the 850-mb level use the initial conditions of surface temperature and pressure. The warmer mean temperature must therefore result from stable conditions within the layer. In the region of the Pacific Anticyclone the most logical explanation of a stable layer is the frequent occurrence of the subsidence inversion.

Woodcock (1940) found that conditions favorable to the formation of cloud bands were related to the wind speed and the air-water temperature difference. The third predictor selected would appear to indicate that the relationship takes the form of the sensible heat transfer. A closer examination of the matrix trace for each of the synoptic variables when the predictor was selected suggests other possible combinations of the same two variables with perhaps a third synoptic parameter. The selection of SNH as a predictor implies this is the best combination of VGS and TWS. For the computation of COMB, the air-dewpoint temperature difference (TSD) is used. The computation of RICH involves the nonlinear combination of three terms in the form of the square of VGS along with TWS. An examination of the value of the matrix trace for each of the parameters when SNH was selected shows that there was very little difference in the value for the parameters TSD, TWS, SNH, COMB, and RICH. It is quite possible that given a higher quality of data the three synoptic variables of VGS, TSD, and TWS combined in the form of COMB would prove to be a more important variable than SNH. In this regard it is important to note that the value of the matrix trace for VGS, when SNH was selected, was one of the lowest of any of the 17 parameters from which it was possible to select a predictor. Quite naturally, after the selection of SNH the position of VGS did not improve. Thus, one can say quite definitely that VGS as an independent variable makes practically no contribution to the discrimination among those groups of cloud bands used in the given sample. It is only when the surface wind speed is combined with the temperature differences that it becomes important. The specific form of this combination has been left somewhat doubtful. For the given set of observations, it was in the form of the sensible heat transfer between the ocean and the atmosphere.

The response obtained from some of the synoptic parameters other than those selected during the screening analysis is also of interest in the interpretation of the results. Of particular interest in this respect is the complete lack of response obtained from the thermal gradient normal to the surface wind (DTN). Kuettner (1959) found that the maximum geostrophic wind quite commonly occurred at the surface of the earth when cloud bands were present. The type of cloud bands he observed were on a much smaller scale than those used in this study. The same type of wind profile in the vertical is quite common in the region of the Pacific Anticyclone, especially in the southern half. The results of this analysis show the lack of importance of DTN in discriminating among the groups of cloud banding used for the given set of observations. In fact, the difference in group means between no bands and small band size for DTN was effectively zero. The value of the matrix trace for DTN when the first predictor was selected was two orders to magnitude lower than that for the predictor selected. This shows the large variance occurring within groups compared to the variance between groups.

During the 1962 period the number of observations of banding was much larger than the number observed in the 1961 period. Not all parts of the region shared in this increase. There were definite zones in which the increase took place while other parts of the region had a decrease in the number of observations from one year to the next. The changes in banding along with those which took place in the distribution of some of the synoptic parameters, especially DTN, are discussed in more detail in Appendix B.

5.4.3 The Discriminant Functions and Specification of Cloud Bands

After the predictors were selected the observations were again separated into two dependent samples according to year. The decision to use two dependent samples when making the specifications was dictated by the limitations on the size of the sample which could be handled by the program using the IBM 7090 computer. The discriminant functions used in making the specifications were also determined independently for each year. The coefficient vectors for each of the discriminant functions are given in Table XIV. The eigenvalue is listed below its associated vector.

The values of λ determined from the 1961 sample indicates little or no discrimination among the groups of band size. This is confirmed by the results for the specification of groups (Table XV). Only four cases were specified to be other than group 1 (no bands).

The two values of λ obtained from the 1962 sample are about the same as those determined when discriminating among groups of cell size. The results of the specifications presented in Table XVI show that the discrimination was between groups 1 and 2 (none and small). Less than 50% of group 2 were specified correctly. The fact that most of the observed group 3 were specified as 1 would indicate that there is no significant difference between the class with no bands and those with large spacing.

TABLE XV

RESULTS FOR THE SPECIFICATION OF BAND SIZE
IN THREE GROUPS FOR THE 1961 PERIOD

Observed	Specified			
	1	2	3	Total
1	420	2	0	422
2	76	2	0	78
3	68	0	0	68
Totals	564	4	0	568
No. Correct = 422, Skill Score = 0.0				

TABLE XVI

RESULTS FOR THE SPECIFICATION OF BAND SIZE
IN THREE GROUPS FOR THE 1962 PERIOD

Observed	Specified			
	1	2	3	Total
1	327	44	0	371
2	86	69	0	155
3	63	19	1	83
Totals	476	132	1	609
No. Correct = 397, Skill Score = 0.12				

The group means and the 50% contour ellipses for the discriminant functions in the 1961 period (Fig. 22) and the 1962 observations (Fig. 23) give a more vivid description of the discrimination accomplished with the two sets. The large dispersion in the value of the second discriminant function for the 1961 observations accounts for the inability to discriminate among cloud banding groups during this period. Figure 23 demonstrates that the differences in the 1962 observations were largely be-

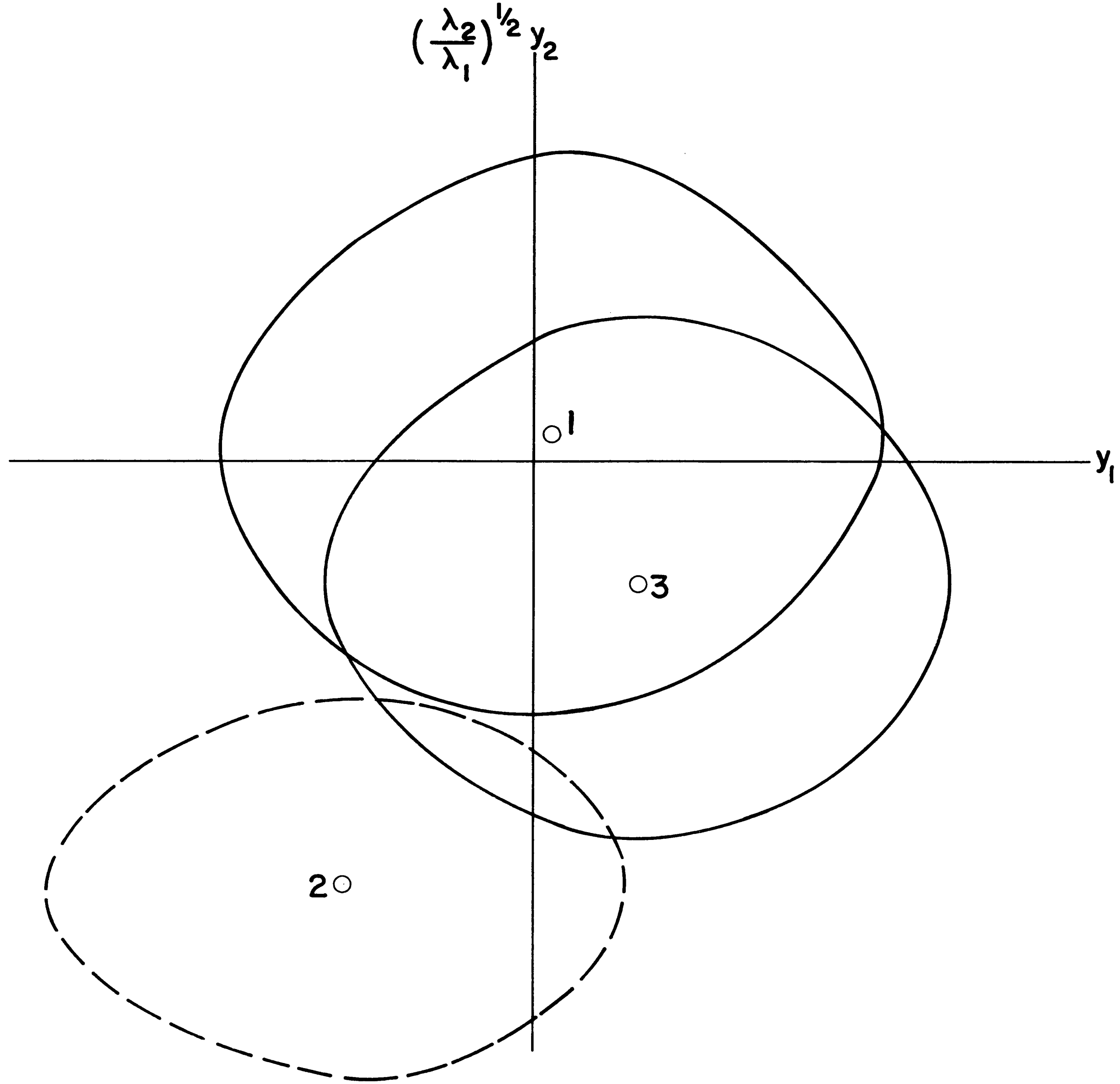

Fig. 22. Mean and 50% contour ellipse of the discriminant functions for each of the three groups of banding in the 1961 sample.

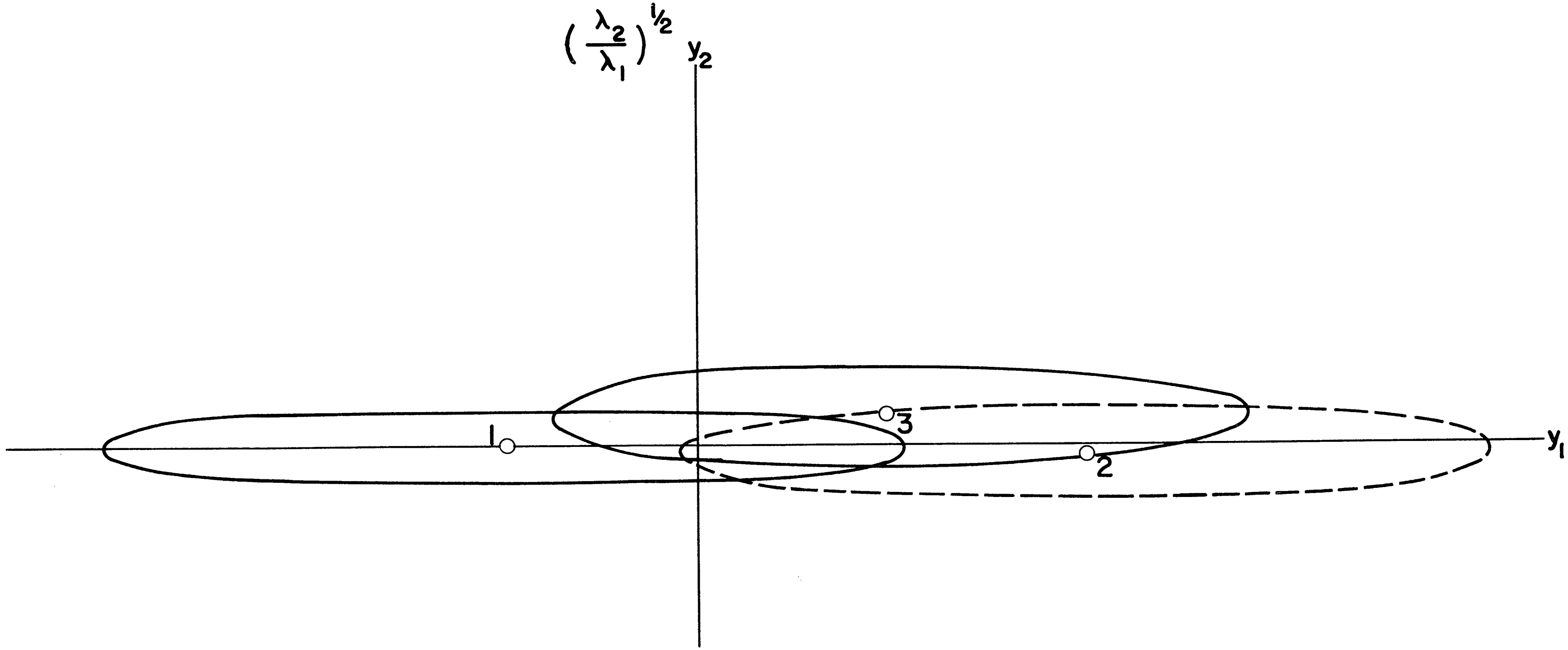

Fig. 23. Mean and 50% contour ellipse of the discriminant functions for each of the three groups of banding in the 1962 sample.

tween the two groups of no bands and those with small size bands.

5.4.4 Summary of Results for Cloud Banding

When the observations for the two time periods were combined into one set it was necessary to eliminate the variable of mean solar time. The location of the observation was an important parameter in the specification of the occurrence of cloud bands. The occurrence of a stable layer between the surface and 850 mb is one of the most important meteorological variables for the determination of the band spacing when it is present. The average value of Z85 indicates that the layer, as a single entity, is more stable when small bands are present than when the skies are completely clear.

The value of the surface wind speed becomes important in the discrimination among groups of cloud bands only in a nonlinear combination with the temperature differences. In this analysis it was in the form of the sensible heat transfer between the ocean and the atmosphere.

It was not possible to specify groups of cloud bands for the observations taken during the 1961 period. The results for the specification of band size in three groups for the 1962 period showed that the discrimination was almost exclusively between those without banding and the group with small size bands.

6. CLOUD PARAMETERS AS SPECIFIERS

6.1 THE SIGNIFICANCE AND THE PROBLEMS

A cursory examination of satellite photographs taken over the ocean areas, on any given day, could reveal the contribution to the utility of meteorological satellite data by being able to specify the values of the environmental meteorological parameters from the cloud patterns.

The results of the previous sections serve to illustrate some of the problems one might entail. When specifying the cloud amount it was found that six of the synoptic parameters used were significant. With the six predictors it was still only possible to specify slightly more than half the observations correctly. The order in which the synoptic parameters were selected indicates a second major problem. The cloud patterns show a much better relationship to the more complex synoptic parameters, e.g., latent heat flux, than to the simpler ones such as the wind speed. The closer the meteorological parameter specified is to the basic meteorological variables such as pressure, temperature, and moisture content, the more useful it will prove to be in the general case.

The inherent redundancy contained in a set of meteorological variables, such as those used in this study, suggests a method whereby the cloud parameters are used to specify those synoptic parameters which show the best relationship. These would then be used to specify the values of the simplest synoptic parameters which are desired. The fallacy in such an approach is that we are not specifying the simple synoptic parameters by using the complex ones as it may seem. Rather, we are simply using a more indirect approach to specify the simple synoptic variable from the cloud parameters. The end result of this indirect approach, averaged over a set of observations, would be the same as if they had been specified directly from the cloud patterns.

An approach to the problem similar to the one just discussed is to specify a consistent set of values for the parameters simultaneously. It was found that the amount of information contained in the variables used to describe the cloud patterns was insufficient to use this method (see Section 7.2 for further details).

Eight synoptic parameters from the list in Table III were selected for a test of the information provided by the cloud patterns. These were U, V, SHR, LTH, SNH, VGS, TSD, and TWS. The list includes six relatively simple variables plus two which are nonlinear combinations of the others.

6.2 OUTLINE OF STATISTICAL METHOD USED

The values of the synoptic variables could have been divided into groups for analysis by the technique of multiple-discriminant analysis used in the previous section. However, since they are continuous, a form of multiple linear regression was deemed to be a more appropriate analysis technique.

The particular form used was a stepwise regression program. The objective of this analysis, as is the case for all forms of regression analysis, is to generate a linear regression equation of the form

$$Y = B_o + \sum_{j=1}^{J} B_j X_j \tag{31}$$

from a set of N observations each consisting of a subset of K independent variables. In the stepwise regression, after the selection of each X_j the X's selected in the previous steps are tested to ensure their validity in the regression equation. It is therefore possible to specify a statistical level of significance for keeping $X_1 \ldots X_{j-1}$, as well as specifying the level of significance which X_j must attain for original entrance in the regression equation. An F level of .05 with (N-1) degrees of freedom, independent of the number of predictors from which it was possible to select X_j, was specified for entering the predictor. The level was specified at .10 with the same number of degrees of freedom for removing the variable from the regression equation. The details for adapting this linear stepwise regression method for use on an electronic computer have been described by Dallemond (1958). The computer program used for the analysis was one available in the computing library at The University of Michigan.

6.3 SPECIFICATION OF SYNOPTIC PARAMETERS FROM THE CLOUD PATTERNS

The test was designed to determine the value of the cloud variables in specifying the values of the synoptic parameters for the quasi-stationary conditions existing in the region of the Pacific Anticyclone. The climatological values for the eight synoptic parameters plus the air temperature were therefore included as possible predictors. The other five possible predictors were cloud amount (AMT), cell size (CSZ), band size (BND), LAT and LNG.

The climatological values for U, V, and VGS were determined from the mean surface pressure pattern for the month of August (Fig. 1). The average values for TSD obtained by combining the two time periods used in this study served as an estimate for the climatological value. Mean water temperatures for the month of August were provided by the Bureau of Commercial Fisheries Biological Laboratory in San Diego, California. These were combined with the mean air temperatures for the same month given in the Climatic Atlas (U.S. Navy, 1956) to obtain the values for TWS.

The results of the regression analysis for the eight synoptic parameters are summarized in Tables XVII-XXIV. In these tables the second column gives X_j selected or removed at the end of step j in the analysis. The third gives the value of the F ratio as a test of statistical significance. The removal of a variable is shown by a negative value of F. The percentage reduction of the original variance as a result of adding or removing X_j is given in the fourth column. The standard deviation (S_Y), after the addition or removal of X_j, is given in the sixth column. The original value for the standard deviation is given at the top of each table. The seventh column in each table gives the value of the coefficient B_j after the completion of step J. The value of the constant term B_0 in Eq. (31) after the completion of step J, is given at the top of each table. The standard deviation of the coefficient B_j after step J is given in the last column.

(An error in the format statement of the computer program resulted in a multiplication of the climatological values of the sensible heat flux by a factor of 10 wherever it appears except in Table XXI.)

TABLE XVII

RESULTS OF REGRESSION ANALYSIS FOR EAST-WEST COMPONENT OF THE SURFACE WIND (U)

(Std. Dev. U = 5.95 msec^{-1}, Final B_o = -23.66)

Step	X_j	F	% Red. Var.	S_u	Final B_j	Final S_B
1	$\overline{U}$	886.2	50.3	4.20	.24	.11
2	$\overline{VGS}$	46.7	52.8	4.09	--	--
3	LAT	18.8	53.8	4.04	.40	.06
4	$\overline{TS}$	10.6	54.3	4.03	.25	.04
5	$\overline{SNH}$	17.8	55.2	3.99	.07	.01
6	$\overline{TSD}$	26.1	56.5	3.94	-.92	.21
7	$\overline{LTH}$	9.0	57.0	3.92	-.09	.02
8	$\overline{VGS}$	-2.3	56.9	3.92	--	--
9	AMT	4.9	57.1	3.92	-.20	.09

TABLE XVIII

RESULTS OF REGRESSION ANALYSIS FOR NORTH-SOUTH COMPONENT OF THE SURFACE WIND (V)

(Std. Dev. V = 4.26 msec^{-1}, Final B_o = -12.36)

Step	X_j	F	% Red. Var.	S_v	Final B_j	Final S_B
1	$\overline{V}$	342.0	28.0	3.61	.52	.06
2	$\overline{TS}$	53.0	32.2	3.51	.24	.03
3	$\overline{TSD}$	14.3	33.2	3.48	-.49	.15
4	BND	10.2	34.0	3.47	-.63	.20
5	$\overline{VGS}$	4.9	34.4	3.46	-.15	.07

TABLE XIX

RESULTS OF REGRESSION ANALYSIS FOR SCALAR DIFFERENCE IN WIND SPEED BETWEEN 850 MB AND SURFACE (SHR)

(Std. Dev. SHR = 3.07 msec^{-1}, Final B_o = 3.04)

Step	X_j	F	% Red. Var.	S_{SHR}	Final B_j	Final S_B
1	$\overline{SHR}$	48.1	5.2	2.99	--	--
2	$\overline{TSD}$	14.5	6.7	2.97	-.46	.07
3	$\overline{V}$	8.3	7.6	2.96	.17	.04
4	$\overline{SHR}$	-2.3	7.4	2.96	--	--

TABLE XX

RESULTS OF REGRESSION ANALYSIS FOR LATENT HEAT FLUX (LTH)

(Std. Dev. LTH = 19.46 cal m^{-2} sec^{-1}, Final B_o = 146.64)

Step	X_j	F	% Red. Var.	S_{LTH}	Final B_j	Final S_B
1	$\overline{LTH}$	526.4	37.5	15.40	1.90	.18
2	$\overline{SHR}$	68.6	42.0	14.84	1.35	.50
3	$\overline{SNH}$	30.5	44.0	14.59	- .32	.05
4	$\overline{TS}$	14.9	44.9	14.48	-1.23	.17
5	LAT	25.5	46.5	14.28	-1.46	.22
6	BND	7.4	47.0	14.23	2.31	.82
7	CSZ	5.6	47.3	14.19	1.56	.47
8	$\overline{VGS}$	4.7	47.6	14.16	-3.15	.84
9	$\overline{U}$	12.1	48.3	14.07	1.66	.40
10	AMT	6.1	48.7	14.03	-1.30	.51
11	$\overline{V}$	5.6	49.0	13.99	.68	.29

TABLE XXI

RESULTS OF REGRESSION ANALYSIS FOR SENSIBLE HEAT FLUX (SNH)

(Std. Dev. SNH = 3.65 cal m^{-2} sec^{-1}, Final B_o = 5.61)

Step	X_j	F	% Red. Var.	S_{SNH}	Final B_j	Final S_B
1	$\overline{U}$	59.1	6.3	3.54	-.18	.08
2	$\overline{TSD}$	29.4	9.4	3.48	-.70	.18
3	$\overline{V}$	6.5	10.0	3.47	.32	.09
4	$\overline{LTH}$	8.6	10.9	3.46	.12	.03
5	LNG	9.2	11.8	3.44	-.05	.01
6	$\overline{SHR}$	6.2	12.5	3.43	.24	.10
7	BND	5.7	13.0	3.42	.48	.20

TABLE XXII

RESULTS OF REGRESSION ANALYSIS FOR SURFACE
GEOSTROPHIC WIND SPEED (VGS)

(Std. Dev. VGS = 3.36 $msec^{-1}$, Final B_o = 31.73)

Step	X_j	F	% Red. Var.	S_{VGS}	Final B_j	Final S_B
1	$\overline{VGS}$	49.5	5.3	3.26	--	--
2	$\overline{U}$	66.9	12.1	3.15	.52	.07
3	$\overline{SHR}$	48.2	16.7	3.07	.38	.08
4	CSZ	11.5	17.7	3.05	.16	.06
5	$\overline{LTH}$	6.5	18.3	3.04	.26	.02
6	$\overline{SNH}$	11.6	19.4	3.02	-.07	.009
7	$\overline{TS}$	17.0	21.0	3.00	-.20	.03
8	LAT	6.9	21.6	2.99	-.14	.04
9	$\overline{VGS}$	-1.5	21.4	2.99	--	--

TABLE XXIII

RESULTS OF REGRESSION ANALYSIS FOR AIR-DEWPOINT TEMPERATURE DIFFERENCE (TSD)

(Std. Dev. TSD = 2.66°F, Final B_o = 10.26)

Step	X_j	F	% Red. Var.	S_{TSD}	Final B_j	Final S_B
1	$\overline{U}$	281.2	24.3	2.32	-.13	.06
2	$\overline{TSD}$	14.7	25.5	2.30	.54	.11
3	$\overline{TS}$	9.0	26.3	2.29	-.07	.02
4	$\overline{LAT}$	5.4	26.7	2.28	-.07	.03

TABLE XXIV

RESULTS OF REGRESSION ANALYSIS FOR WATER-AIR TEMPERATURE DIFFERENCE (TWS)

(Std. Dev. TWS = 1.93°F, Final B_o = 2.70)

Step	X_j	F	% Red. Var.	S_{TWS}	Final B_j	Final S_B
1	$\overline{U}$	62.0	6.6	1.87	-.19	.04
2	$\overline{TSD}$	36.7	10.4	1.83	-.48	.09
3	$\overline{V}$	10.2	11.4	1.82	.09	.02
4	BND	8.3	12.2	1.82	.31	.11
5	$\overline{LTH}$	6.5	12.9	1.81	.03	.01

These results show that the percentage of the variance explained ranged from 7.4 for SHR to 57.1 for the U-component of the surface wind. It should be noted that in most cases the major portion of the explained variance was contributed by the climatological value of the parameter to be specified. In the case of the variable U it was found that $\overline{U}$ alone achieved a 50.3% reduction in the variance. For LTH, the climatological value at the observation point succeeded in reducing the variance by 37.5%.

The major factor which the results have in common is the lack of any important contribution by the cloud parameters. For the synoptic variables SHR and TSD, none of the three cloud parameters were included in the regression equation. In the case of three of the synoptic variables, V, VGS, and TWS, one of the cloud variables was the fourth specifier selected. In none of the eight cases was any cloud parameter higher than fourth. The only case in which more than one of the cloud variables appears is in the regression equation for LTH where all three were selected.

In the case of the regression equation for LTH (Table XX), the three cloud variables combined to explain only 1.3% of the variance. In spite of this low contribution, the equation for LTH should be among the best in improvement over climatology of any of the eight variables. The variance was reduced by 11.5% over and above that of climatology. The only one higher than this was VGS where the variance was reduced by 21.4% without the climatological value. The reduction is primarily due to the interrelationship existing between $\overline{VGS}$ and the other synoptic variables in this set. On two occasions, U and VGS, $\overline{VGS}$ was selected and later removed from the regression equation.

The results presented in Tables XVII-XIV have shown that any improvement over climatology would be small in most of the eight cases. To achieve a more quantitative estimate of this improvement the eight synoptic parameters were specified with the regression equations using both the dependent data from the 1961 period and the independent data from the 1962 period. The standard deviation about the observed value, as well as the mean value of the absolute error for both the regression and the climatological values are shown in Table XXV.

The results for the dependent and independent data samples are almost exactly the same in all cases. The values specified by the regression equations show no improvement over climatology for the variables, V, U, SHR, and TSD. The values specified by the regression equations for LTH, TWS, and SNH showed approximately a 20% reduction in the mean value of the absolute error. In the case of VGS this reduction amounted to 11%.

The results obtained under the quasi-stationary conditions of the Pacific Anticyclone give some indication of the results one might expect to achieve by using the same type of analysis with the cloud patterns in the migratory anticyclones. In this case the climatological value at the observation point would explain a much smaller percentage of the variance. The effect would, of course, also show up in the climatological values of the synoptic variables other than the one being specified. These two effects should tend to cancel one another. As a result the total percentage of the variance explained would be less but the improvement over climatology should be about the same as that achieved under the more or less stationary conditions.

A very important consideration is to be found in a comparison of the results of this section with those obtained in the previous section. The amount of information contained in a linear combination of the three cloud variables is much less than the sum of the information available when the three are considered individually. A more detailed discussion of this aspect of the cloud variables is given in Section 7.2.

TABLE XXV

RESULTS OF REGRESSION ANALYSIS FOR DEPENDENT AND INDEPENDENT DATA

Variable	Dependent Data (1961)					Independent Data (1962)				
	Regression		Climatology		Change in Absolute Error	Regression		Climatology		Change in Absolute Error
	Std. Dev.	Abs. Error	Std. Dev.	Abs. Error		Std. Dev.	Abs. Error	Std. Dev.	Abs. Error	
U	3.9	2.9	4.3	3.3	-0.4	4.2	3.2	3.8	2.9	+0.3
V	3.4	2.5	3.7	2.6	-0.1	3.6	2.6	3.6	2.6	0
SHR	4.0	3.4	3.6	2.9	+0.5	3.6	2.9	3.5	2.7	+0.2
LTH	13.9	10.2	17.7	12.9	-2.7	12.8	10.1	16.4	12.8	-2.7
SNH	3.4	2.3	4.2	2.9	-0.6	3.6	2.4	4.2	2.9	-0.5
VGS	3.0	2.3	3.9	2.8	-0.5	3.0	2.3	3.5	2.6	-0.3
TSD	2.3	1.8	2.3	1.9	-0.1	2.2	1.7	2.1	1.6	+0.1
TWS	1.8	1.4	2.6	2.0	-0.6	1.9	1.4	2.4	1.9	-0.5

7. FURTHER ANALYSIS OF THE INFORMATION CONTAINED IN THE CLOUD PATTERNS

7.1 PRELIMINARY REMARKS

Interactions of a number of meteorological variables when associated with the various cloud patterns complicates the task of specifying values for individual meteorological parameters. The quasi-stationary conditions within most of the Pacific Anticyclone adds further complications to the task. Still another reason for the lack of success in specifying the meteorological parameters by using the cloud variables could be due to an inadequate description of the cloud patterns. The remainder of this section is concerned with the discussion of the difficulties in more quantitative terms.

In the screening analysis for selecting significant predictors for the cloud patterns the latitude and longitude were among the most important predictors. Their importance to the specification of the meteorological parameters was no less than for the cloud variables. In this case the effects were present in a more indirect manner in that one or both had substitutes in the form of climatological values. To make the contribution of the latitude and longitude to both the cloud and meteorological variables more explicit we make use of an analysis procedure known as canonical correlation.

7.2 CANONICAL CORRELATION AS AN ANALYSIS TECHNIQUE

A method for determining the linear relationship which exists between two sets of variables is known as canonical correlation (cf., James and Shorr, 1959; Cooley and Lohnes, 1962). Given a set of variables with p predictors and q predictands, one can form the matrix R of intercorrelations for the p+q variables. The analysis involves the partitioning of R into four submatrices:

$$R = \begin{pmatrix} R_{11} & R_{12} \\ R_{21} & R_{22} \end{pmatrix} \tag{32}$$

where

R_{11} = intercorrelations among the p predictors;

R_{22} = intercorrelations among the q predictands;

R_{12} = intercorrelations of predictors with predictands; and

R_{21} = the transpose of R_{12}.

The partitioned portions of R are substituted into the following equation:

$$(R_{22}^{-1} R_{21} R_{11}^{-1} R_{12} - L_j I)M_j = 0 . \tag{33}$$

The solution involves finding eigenvalues L for which the determinantal equation $|R_{22}^{-1} R_{21} R_{11}^{-1} R_{12} - L I| = 0$. The nonsymmetric matrix $R_{22}^{-1} R_{21} R_{11}^{-1} R_{12}$ can be written in the form $W^{-1}B$ where

$$W^{-1} = R_{22}^{-1}$$

$$B = R_{21} R_{11}^{-1} R_{12} . \tag{34}$$

The same procedure as that used for finding solutions to the nonsymmetric matrix in discriminant analysis (see Section 5.1) can then be used for determining the eigenvalues and eigenvectors of the nonsymmetric matrix.

The largest eigenvalue for the determinantal equation is the square of the maximum possible correlation between linear combinations of the two sets of variables. The canonical correlation R_c between the jth linear combination of the two sets of variables is $L_j^{1/2}$. The statistical significance of the canonical correlations is tested by a χ^2 test where

$$\chi^2 = - [N-0.5(p+q+1)]\ln \nu \tag{35}$$

where ν is defined as

$$\nu = \prod_{i=r+1}^{q} (1-L_i); \qquad \text{for } q < p \tag{36}$$

in which case r values of the eigenvalues have already been tested and removed. χ^2 is then distributed with (p-r) (q-r) degrees of freedom. The tests reveal the number of linear combinations which allow for statistical interpretation.

We shall first of all be concerned with the maximum value of the canonical correlation coefficient obtained when the number of predictors and predictands is successively reduced. The interpretation can be greatly simplified by a suitable transformation of the X's and Y's to reduce R_{cmax} to an ordinary correlation coefficient.

Let

$$\hat{X}_j = \sum_{p=1}^{P} a_{pj} X_p \tag{37}$$

and

$$\hat{Y}_j = \sum_{q=1}^{Q} b_{qj} Y_q \tag{38}$$

where the vector of coefficients a_{pj} is obtained from:

$$a_{pj} = (R_{11}^{-1} R_{12} b_{qj})/R_{cj} \tag{39}$$

and each vector of b_{qj} is the eigenvector associated with each L_j in Eq. (33).

R_{cj} is the ordinary correlation coefficient between $\hat{X}_j$ and $\hat{Y}_j$. Specifically, R_{cmax}^2 gives the percentage of the variance in $\hat{Y}_1$ explained by $\hat{X}_1$.

7.3 ANALYSIS OF INFORMATION CONTENT

The correlation matrix used in the analyses is shown in Table XXVI. This matrix gives the values for all the intercorrelations among the eight meteorological variables used in Section 6.3 and the three cloud variables plus latitude and longitude. The correlation coefficients were determined from the 1741 observations obtained by combining the two time periods into one set.

Several analyses were made using first the entire correlation maxtrix and then different portions of it. When the whole matrix was used there were five different X's consisting of the three cloud variables plus latitude and longitude. A second analysis excluded latitude and longitude as predictors. The third analysis used only the three cloud variables as predictors and those four predictands which achieved the most success in Section 6.3, i.e., LTH, SNH, VGS, and TWS. A summary of the results obtained from the analyses is given in Tables XXVII-XXIX.

Examining, first of all, the maximum canonical correlation coefficient it can be seen that in each case it is highly significant. Squaring the value of R_{c1} in Table XXVII shows that $\hat{X}_1$ explains more than 60% of the variance in $\hat{Y}_1$. When the latitude and longitude are excluded the amount of the variance explained by $\hat{X}_1$ drops to less than 12%. At least 2/3 of this explained variance in the latter case is associated with the four meteorological variables LTH, SNH, VGS, and TWS. This is found by R^2_{c1} in Table XXIX. Quite clearly then, at least 50% of the variance in the eight meteorological variables is connected with the geographical location or the location within the region of the Pacific Anticyclone. Therefore, in order for this method to be useful with migratory anticyclones it must be possible to define the center of the system from the cloud pattern. Investigations into the capabilities for this type of determination from the cloud pictures have not been accomplished to my knowledge.

Since all five of the canonical correlation coefficients in Table XXVII are statistically significant there are five linear combinations of the predictors and predictands. The vector of coefficients in the table, i.e., values of a_{pj}, makes $\hat{X}_1$ weighted predominately by the latitude and $\hat{X}_2$ by the longitude. The coefficients for the cloud variables do not allow for any significant contribution by these parameters until

TABLE XXVI

CORRELATION MATRIX DETERMINED FOR THE THREE CLOUD VARIABLES, LATITUDE, LONGITUDE, AND EIGHT SYNOPTIC PARAMETERS AS DETERMINED FROM THE COMBINED SET OF OBSERVATIONS FOR THE 1961 AND 1962 PERIODS

Variable	CSZ	BND	LAT	LNG	U	V	SHR	LTH	SNH	VGS	TSD	TWS
AMT	.68	.16	.25	-.22	.11	-.17	.06	-.10	*	.12	-.21	*
CSZ		.09	.17	-.08	.09	-.07	.10	*	.10	.11	-.12	.06
BND			*	-.09	-.06	-.10	*	*	.12	*	-.06	.12
LAT				-.09	.68	-.09	.14	-.61	-.23	*	-.34	-.21
LNG					.06	.56	.16	.08	*	-.13	*	*
U						.08	.32	-.60	-.32	-.06	-.41	-.28
V							.13	-.06	-.10	-.18	-.06	-.10
SHR								-.32	*	-.47	-.07	*
LTH									.44	.52	.48	.38
SNH										*	-.06	.90
VGS											-.11	*
TSD												-.08

*|r| < .06

TABLE XXVII

RESULTS OF CANONICAL CORRELATION ANALYSIS OF FIVE PREDICTORS WITH EIGHT PREDICTANDS

j	R_{cj}	χ^2	$\chi^2_{.05}$	a_{pj}					b_{qj}							
				AMT	CSZ	BND	LAT	LNG	U	V	SHR	LTH	SNH	VGS	TSD	TWS
1	.78	2550.0	55.8	-.05	.07	.06	-.97	.23	-.39	.21	.07	.77	-.28	-.34	-.08	.10
2	.59	911.0	41.3	-.14	.07	-.09	.33	.93	.52	.73	.04	.35	-.13	-.23	-.05	.11
3	.27	169.0	28.9	.55	.73	.24	-.18	.26	.12	-.04	-.45	.11	-.64	-.49	.13	.32
4	.11	42.1	18.3	-.58	.68	-.40	.01	-.19	.37	-.07	.20	-.12	.28	.39	.72	-.21
5	.11	19.9	9.5	-.70	.45	.54	.12	-.07	-.45	.14	.20	-.32	.24	.35	-.03	-.68

TABLE XXVIII

RESULTS OF CANONICAL CORRELATION ANALYSIS OF THREE PREDICTORS WITH EIGHT PREDICTANDS

j	R_{cj}	χ^2	$\chi^2_{.05}$	a_{pj}			b_{qj}							
				AMT	CSZ	BND	U	V	SHR	LTH	SNH	VGS	TDS	TWS
1	.34	318.6	36.4	.993	-.01	.12	.11	.24	-.23	.50	-.53	-.50	.09	.30
2	.19	99.6	23.7	-.56	.83	.001	.35	.31	.49	.30	.52	.35	.24	-.09
3	.15	37.5	12.6	-.29	.03	.96	-.23	-.27	-.14	.46	-.24	-.40	-.36	.54

TABLE XXIX

RESULTS OF CANONICAL CORRELATION ANALYSIS OF THREE PREDICTORS WITH FOUR PREDICTANDS

j	R_{cj}	χ^2	$\chi^2_{.05}$	a_{pj}			b_{qj}			
				AMT	CSZ	BND	LTH	SNH	VGS	TWS
1	.29	205.4	21.0	.999	-.01	.04	-.57	.60	.48	-.29
2	.16	47.4	12.6	-.54	.64	.54	.51	.68	.04	.52
3	.05	5.2	6.0	.41	-.76	.50	-.26	-.55	-.06	.79

$\hat{X}_3$, when R_c has dropped to about 1/3 of its original value.

The three canonical correlation coefficients are all statistically significant when there are eight meteorological variables (Table XXVIII). However, only two are significant when the number of meteorological variables is reduced to four (Table XXIX). There are only two linear combinations of the three cloud variables and the four meteorological predictors LTH, SNH, VGS, and TWS which can be considered significant. For both four and eight predictands, $\hat{X}_1$ consists almost exclusively of AMT which has a coefficient greater than 0.99. The domination of $\hat{X}_3$, in Table XXVIII, by BND is almost as great. However, R_{c3} is less than 50% of the value of R_{c1} so that the influence of BND is much smaller.

There are at least three factors in Tables XXVIII and XXIX which, when taken together, point to existing deficiencies in the cloud analysis scheme insofar as using them to specify other meteorological parameters is concerned. These are:

1. $\hat{X}_1$ is made up almost exclusively of AMT in both cases.

2. R_{c2} drops to nearly 1/2 the value of R_{c1}.

3. R_{c3} in Table XXIX is not statistically significant.

The preponderance of the information available for this set of cloud variables is contained in the cloud amount. It is of particular significance that when CSZ has a relatively large coefficient, AMT has one nearly as large but with the opposite sign. The correlation matrix (Table XXVI) shows that these two variables have a high positive correlation. The result is that much of the contribution by CSZ is canceled by AMT.

A significant correlation between AMT and CSZ when the groups of clear and overcast are included in AMT is to be expected. However, a correlation coefficient of .68 between CSZ and AMT together with the results shown in Tables XXVIII and XXIX lends strong evidence to a conclusion that the three cloud variables are really only giving one significant piece of information to the specification of the meterological variables. This is contained in the amount of clouds present. If this is indeed the case, then a different approach to the classification of the cloud patterns is the first requirement before a major improvement in the ability to obtain quantitative information from them can hope to be achieved.

8. CONCLUSIONS

This analysis has shown that significant statistical relationships exist between the parameters used to describe the low-level cumuliform cloud patterns and the values of the other meteorological variables in the lower layers of the atmosphere. The nature of the relationships is such that a given cloud variable is dependent upon the values of a number of meteorological parameters.

The existence of zones within an anticyclone where specific cloud patterns are predominant makes the relative location of the observation one of the most important quantities. In the quasi-stationary conditions of the Pacific Anticyclone the location can be specified by the latitude and longitude. When the cloud patterns are associated with migratory anticyclones a set of coordinates moving with the system would be required.

The amount of cloud cover, when classified in one of six groups, was found to be dependent upon the latent heat transfer between the ocean surface and the atmosphere, the air-dewpoint temperature difference at the surface and the scalar difference in geostrophic wind speed between the 850-mb level and the surface. When the observations of cloud amount were combined into the three groups of mostly clear, partly cloudy and cloudy the importance of the geographical location compared to that of the meteorological predictors was reduced. The magnitude of the surface geostrophic wind speed was selected instead of the air-dewpoint temperature difference when only three groups were used.

The amount of moisture in the surface layers of the atmosphere is important in determining the amount of cloud cover present in the range from scattered to broken. The largest value of the air-dewpoint temperature difference occurs with the presence of scattered cloud cover. The latent heat transfer is also a maximum when associated with this amount of cloud cover.

The lowest values of the surface geostrophic wind speed occur with clear skies or only a few clouds. Cloud amounts in the range from scattered through broken are associated with a nearly uniform mean wind speed of approximately 7 m sec^{-1}. An increase in cloud cover to mostly overcast skies has an associated increase in the mean value of the wind speed.

The size of cumulus cells is determined primarily by the structure of the wind field in the lowest 5000 ft of the atmosphere. The importance of the wind shear to this determination was shown by the selection of both the scalar and vector difference in the geostrophic wind between the 850-mb level and the surface.

Discrimination among the three groups of specific cell size was very good. A classification scheme based on the predominant cell size and elimination of the group classed as mixed would have improved the results obtained. A bias toward the smaller cell sizes induced in the 1962 set of observations precluded any valid comparisons between the two time periods.

Discrimination among groups of cloud bands was not nearly as satisfactory as that among the other cloud variables. There appear to be small differences between those meteorological conditions existing when large bands are present and those when there are no bands present in the cloud pattern. The presence of small bands indicates that the layer between the surface and the 850-mb level is more stable than normal, perhaps due to a subsidence inversion between the two levels. Small bands are also related to the combination of the geostrophic wind speed and the temperature differences. In this analysis the relationship took the form of the sensible heat transfer between the ocean surface and the atmosphere.

The ability to specify the cloud parameters in groups from the observed values of the meteorological predictors varied over a fairly wide range for the percentage correct. In terms of the simple skill score the values ranged from zero for the 1961 sample of cloud bands to 0.28 for the dependent sample of cloud amount in three groups. A feature common to each of the cloud parameters was the large spread of the points about the vector means of the discriminant function. (This was the result of a substantial amount of noise in the observations.)

No single meteorological parameter was found to be predominant in determining the groups of the cloud variables. The degree of success in obtaining quantitative information from the cloud patterns is therefore dependent upon the ability to specify the values for a set of meteorological parameters. The information contained in the terms used to describe the cloud patterns was not adequate for this type of specification.

Useful information about the cloud patterns was principally contained in the cloud amount. At least 50% of the variance in a set of eight meteorological variables could be attributed to the geographical location or the location within the region of the Pacific Anticyclone. In order to obtain quantitative information from the cloud patterns associated with migratory anticyclones it must be possible to define the center of the system by using the clouds.

9. SUGGESTIONS FOR FUTURE RESEARCH

A net gain over the results achieved in the present investigation will be realized only with the use of more objective techniques for the original description of the cloud patterns, along with an improved quality in the other meteorological data. Information obtained from the cell size and band spacing could be enhanced by slight modifications to the two-dimensional spectral analysis technique. These changes or additions would include the use of numerical filters to obtain useful data about the organization in the cloud patterns on different scales.

It is anticipated that future meteorological satellites will provide pictures having a nadir angle near zero, a resolution of approximately 1 mi, and a gray scale with both an enhanced resolution and less variability among pictures. The use of the improved data with the modified spectral analysis should prove capable of providing information about the cloud patterns on at least three scales, e.g., synoptic ($L > 50$ mi), meso ($10 < L < 50$ mi) and submeso ($L < 10$ mi). The information provided by the cloud amount could also be enhanced by an objective technique using at least 10 groups. The basis for such a technique could be provided by a simple frequency distribution of the gray scale above and below a predetermined value.

Future research on the information content of the cloud patterns should utilize meteorological data, both surface and upper air, obtained concurrently with the cloud pictures. A set of data could be provided in a relatively short period by special observations from ships taken at the time the satellite passes. Given such a concurrent set of data an analysis of the information contained in the cloud patterns should then be made utilizing more sophisticated statistical techniques than was done in the present study. Specifically, a definite answer should be sought for the question: What synoptic variables can be determined from a description of the cloud patterns, and further, within what quantitative range is it possible to specify their values?

The cycle of development and life span of the cumulus cloud groups, and the relationship, if any, between the brightness of a cumulus cloud and its other physical characteristics are two areas in which our knowledge is lacking. It is suggested that photographic equipment used with a constant-level balloon at an altitude of approximately 100,000 ft could make a valuable contribution in both areas. The cloud group dimensions occur in the range of a few miles up to 50 mi. The time period of the life cycle has been suggested to be on the order of a few hours. First approximations show that, if this is the case, the wind speed at the altitude of the balloon must be relatively low to obtain useful information about the life cycle.

APPENDIX A

DISTRIBUTION OF OBSERVATIONS WITHIN 5° LATITUDE AND LONGITUDE "SQUARES"

TABLE A-I

FREQUENCY DISTRIBUTION OF CLOUD AMOUNT

TIROS III, AUGUST 15, TO SEPTEMBER 5, 1961

		LONGITUDE(W)												
LAT	AMT	180	175	170	165	160	155	150	145	140	135	130	125	120
50	1	0	0	0	0	0	0	0	0	0	0	0	0	0
	2	0	0	0	1	0	0	1	0	0	0	0	0	0
	3	0	0	0	0	0	1	2	0	1	1	0	0	0
	4	0	0	0	0	0	0	0	0	0	0	0	0	0
	5	0	0	0	0	0	0	1	0	0	0	0	0	0
	6	0	0	0	1	3	2	0	1	1	1	0	0	0
45	1	0	0	0	0	0	0	0	0	0	0	1	1	0
	2	0	1	1	1	0	0	0	1	0	1	0	3	0
	3	0	0	1	0	2	1	2	2	2	1	0	0	0
	4	0	0	0	0	0	1	0	0	0	0	0	0	0
	5	0	0	0	1	1	1	3	0	3	0	1	0	0
	6	1	2	8	4	5	4	0	3	3	3	7	0	0
40	1	1	0	0	0	0	2	1	0	0	2	4	4	0
	2	0	0	1	1	1	3	3	1	0	3	2	6	0
	3	1	3	3	3	4	1	3	3	2	1	3	1	0
	4	0	2	0	1	0	0	0	1	0	0	0	0	0
	5	1	3	3	2	2	2	3	2	3	1	2	0	0
	6	1	2	2	1	1	3	4	3	5	7	7	3	0
35	1	0	1	3	0	2	3	1	0	0	0	4	6	1
	2	3	5	6	3	9	5	5	3	2	3	3	1	0
	3	0	0	6	5	7	2	2	4	2	2	3	0	0
	4	1	1	0	0	0	0	0	1	1	0	0	0	0
	5	0	1	0	0	1	1	0	3	5	2	2	0	0
	6	0	0	0	0	0	1	4	4	3	3	1	4	3
30	1	4	4	1	0	3	3	3	0	1	3	5	3	3
	2	4	7	18	12	8	6	11	3	4	2	5	6	1
	3	2	5	8	4	7	4	6	7	5	2	3	1	0
	4	0	0	1	0	0	0	3	1	0	2	3	0	0
	5	0	0	0	0	1	0	3	0	2	0	4	1	1
	6	0	0	1	0	0	0	0	4	3	0	4	3	6
25	1	0	2	0	0	1	0	0	0	5	3	1	1	0
	2	2	4	9	6	7	6	7	4	6	2	4	2	0
	3	2	4	5	1	6	6	7	5	2	2	3	0	0
	4	0	0	0	0	0	0	0	0	1	0	0	0	0
	5	0	0	0	0	0	0	0	0	1	1	1	3	0
	6	0	0	1	2	0	0	0	0	1	2	2	2	0
20	1	0	1	0	0	0	0	0	0	1	0	0	0	0
	2	0	1	7	7	10	2	6	2	4	3	3	1	0
	3	0	1	7	5	7	14	10	7	10	9	5	2	1
	4	0	0	1	0	1	0	0	1	2	0	0	1	0
	5	0	0	0	0	1	1	1	0	4	1	8	2	0
	6	0	0	1	0	0	0	0	0	5	4	3	4	0

CCDE FCR CLCUC AMCUNT

1 CLR	2 CLR TO SCTD
3 SCTD	4 SCTD TO BRKN
5 BRKN	6 BRKN TO OVC AND OVC

TABLE A-II

FREQUENCY DISTRIBUTION OF CELL SIZE

TIROS III, AUGUST 15, TO SEPTEMBER 5, 1961

LAT	SIZE	LONGITUDE (W) 180	175	170	165	160	155	150	145	140	135	130	125	120
50	1	0	0	0	1	0	0	1	0	0	0	0	0	0
	2	0	0	0	0	0	1	0	0	0	0	0	0	0
	3	0	0	0	0	0	0	1	0	0	0	0	0	0
	4	0	0	0	0	0	0	1	0	1	0	0	0	0
	5	0	0	0	0	0	0	1	1	0	1	0	0	0
	6	0	0	0	1	3	2	0	0	1	1	0	0	0
45	1	0	0	1	0	0	0	0	1	0	1	1	2	0
	2	0	0	0	0	0	0	0	0	0	0	0	0	0
	3	0	1	0	0	0	0	0	0	0	0	1	2	0
	4	0	0	2	2	3	1	3	3	3	1	1	0	0
	5	0	0	0	0	0	2	2	0	2	1	0	0	0
	6	1	2	7	4	5	4	0	2	3	2	6	0	0
40	1	1	0	0	0	1	5	2	1	0	2	4	6	0
	2	0	0	0	0	0	0	2	1	0	2	1	1	0
	3	0	0	2	1	0	0	0	1	0	1	2	4	0
	4	1	5	0	4	5	2	5	3	3	0	3	0	0
	5	1	3	5	2	1	1	1	2	4	2	2	0	0
	6	1	2	2	1	1	3	4	2	3	7	6	3	0
35	1	2	4	7	2	6	4	3	1	0	0	5	6	1
	2	0	0	0	1	2	2	3	2	3	3	1	1	0
	3	0	1	3	3	4	2	2	2	1	3	2	1	0
	4	0	1	1	0	4	2	1	2	1	0	3	0	0
	5	2	2	4	2	3	1	0	4	5	2	1	0	0
	6	0	0	0	0	0	1	3	4	3	2	1	3	3
30	1	5	5	3	5	5	7	8	1	2	4	6	4	4
	2	3	7	14	5	2	3	2	3	3	1	4	3	0
	3	0	0	8	4	7	3	7	1	3	0	5	3	0
	4	0	1	0	1	1	0	2	1	2	2	2	1	0
	5	2	3	3	1	4	0	7	6	3	2	3	1	1
	6	0	0	1	0	0	0	0	3	2	0	4	2	6
25	1	1	4	2	1	4	0	0	2	6	5	1	1	0
	2	3	6	10	5	5	3	2	1	4	1	1	1	0
	3	0	0	2	1	2	5	5	2	2	1	5	1	0
	4	0	0	0	0	1	2	1	1	2	0	1	3	0
	5	0	0	0	0	2	2	6	3	1	1	1	1	0
	6	0	0	1	2	0	0	0	0	1	2	2	1	0
20	1	0	1	3	2	0	0	2	0	3	0	1	0	0
	2	0	2	3	5	6	4	4	2	1	1	2	0	0
	3	0	0	2	2	4	5	3	3	5	4	3	3	0
	4	0	0	1	2	3	3	2	3	8	6	8	3	0
	5	0	0	6	1	6	5	6	2	4	2	2	1	1
	6	0	0	1	0	0	0	0	0	5	4	3	3	0

CODE FOR CELL SIZE

1 NONE	4 LARGE
2 SMALL	5 MIXED
3 MEDIUM	6 UNDETERMINED

TABLE A-III

FREQUENCY DISTRIBUTION OF BAND SIZE

TIROS III, AUGUST 15, TO SEPTEMBER 5, 1961

			LONGITUDE(W)												
LAT	BAND		180	175	170	165	160	155	150	145	140	135	130	125	120
50	1	*	0	0	0	0	1	0	1	1	1	1	1	0	0
	2	*	0	0	0	0	0	2	5	1	2	0	0	0	0
	3	*	0	0	0	0	0	0	1	1	1	0	0	0	0
45	1	*	0	0	0	1	3	0	0	3	5	2	5	5	0
	2	*	0	0	0	2	3	3	4	1	2	3	3	1	0
	3	*	0	0	1	1	0	1	2	1	2	0	1	1	0
40	1	*	1	0	3	5	10	11	8	6	13	9	10	10	0
	2	*	0	0	0	3	4	1	3	3	4	1	8	2	0
	3	*	1	1	2	1	0	1	2	0	1	0	3	0	0
35	1	*	1	4	9	6	16	8	14	6	12	9	12	6	3
	2	*	0	0	3	3	1	0	1	1	1	0	5	2	0
	3	*	2	0	1	0	0	1	3	1	0	3	3	0	0
30	1	*	5	8	13	16	16	14	15	12	15	9	13	8	1
	2	*	0	1	1	1	3	1	1	0	3	1	8	6	4
	3	*	1	0	3	0	0	1	1	3	7	5	2	0	0
25	1	*	7	6	11	8	13	11	11	11	5	4	6	5	1
	2	*	2	1	1	0	1	0	2	1	4	1	6	3	1
	3	*	0	0	0	0	0	0	1	0	1	1	0	0	0
20	1	*	0	16	21	17	25	17	22	11	15	5	7	2	0
	2	*	0	0	1	1	1	3	1	1	3	4	7	2	0
	3	*	0	0	1	0	1	0	3	4	3	2	3	1	0

CODE FOR BAND SIZE
1 NONE 2 SMALL 3 LARGE

TABLE A-IV

FREQUENCY DISTRIBUTION OF CLOUD AMOUNT

TIROS V, AUGUST 15, TO SEPTEMBER 5, 1962

			LONGITUDE(W)												
LAT	AMT		180	175	170	165	160	155	150	145	140	135	130	125	120
50	1	*	0	0	0	0	0	0	0	0	0	0	0	0	0
	2	*	0	0	0	0	0	0	0	0	0	0	0	0	0
	3	*	0	0	0	0	0	0	1	0	0	0	0	0	0
	4	*	0	0	0	0	0	1	3	1	2	0	0	0	0
	5	*	0	0	0	0	0	1	3	1	1	0	0	0	0
	6	*	0	0	0	0	1	0	0	1	1	1	1	0	0
45	1	*	0	0	0	0	0	0	0	1	1	1	0	1	0
	2	*	0	0	0	0	1	1	0	1	2	0	1	2	0
	3	*	0	0	0	0	0	0	2	0	1	1	2	0	0
	4	*	0	0	1	3	2	1	2	1	0	1	2	1	0
	5	*	0	0	0	1	2	2	2	2	3	1	1	2	0
	6	*	0	0	0	0	1	0	0	0	2	1	3	1	0
40	1	*	0	0	0	2	1	1	0	0	1	0	0	2	0
	2	*	0	0	2	2	2	4	1	0	5	2	2	7	0
	3	*	1	0	3	4	5	5	5	5	4	4	6	0	0
	4	*	0	0	0	0	3	1	2	1	2	0	1	0	0
	5	*	1	1	0	1	3	1	4	1	2	3	9	1	0
	6	*	0	0	0	0	0	1	1	2	4	1	3	2	0
35	1	*	0	0	1	2	2	0	1	0	3	1	1	4	3
	2	*	2	1	5	3	9	3	4	5	5	4	9	0	0
	3	*	0	1	5	2	4	4	8	3	5	4	3	0	0
	4	*	1	0	1	1	1	1	3	0	0	1	3	1	0
	5	*	0	1	0	0	1	1	0	0	0	2	3	1	0
	6	*	0	1	1	1	0	0	2	0	0	0	1	2	0
30	1	*	0	0	0	0	0	0	1	1	0	3	4	5	1
	2	*	6	5	9	11	10	9	5	6	9	1	9	2	0
	3	*	0	2	5	5	7	6	11	7	14	7	4	1	0
	4	*	0	1	2	0	1	0	0	0	2	0	1	1	0
	5	*	0	0	1	0	0	1	0	1	0	2	2	3	3
	6	*	0	1	0	1	1	0	0	0	0	2	3	2	1
25	1	*	0	1	1	1	2	2	0	0	0	1	3	2	1
	2	*	7	3	6	6	6	6	5	5	2	1	1	1	0
	3	*	1	3	4	1	6	3	9	6	5	1	1	0	0
	4	*	1	0	1	0	0	0	0	1	2	1	4	0	0
	5	*	0	0	0	0	0	0	0	0	0	0	1	0	0
	6	*	0	0	0	0	0	0	0	0	1	2	2	5	1
20	1	*	0	1	3	1	0	0	0	0	0	0	2	1	0
	2	*	0	11	14	13	18	10	12	3	7	1	0	1	0
	3	*	0	3	6	3	9	10	11	9	4	1	3	0	0
	4	*	0	0	0	1	0	0	3	1	1	0	1	1	0
	5	*	0	0	0	0	0	0	0	2	3	3	4	0	0
	6	*	0	1	0	0	0	0	0	1	6	6	7	2	0

CODE FOR CLOUD AMOUNT

1 CLR	2 CLR TO SCTD
3 SCTD	4 SCTD TO BRKN
5 BRKN	6 BRKN TO OVC AND OVC

TABLE A-V

FREQUENCY DISTRIBUTION OF CELL SIZE

TIROS V, AUGUST 15, TO SEPTEMBER 5, 1962

LONGITUDE(W)

LAT	SIZE		180	175	170	165	160	155	150	145	140	135	130	125	120
50	1	*	0	0	0	0	0	0	0	0	0	0	0	0	0
	2	*	0	0	0	0	0	0	5	1	1	0	0	0	0
	3	*	0	0	0	0	1	0	1	0	1	0	0	0	0
	4	*	0	0	0	0	0	0	0	0	0	0	0	0	0
	5	*	0	0	0	0	0	2	1	2	2	0	0	0	0
	6	*	0	0	0	0	0	0	0	0	0	1	1	0	0
45	1	*	0	0	0	0	1	0	0	1	3	1	1	2	0
	2	*	0	0	0	1	1	1	1	1	2	3	2	1	0
	3	*	0	0	0	2	3	1	0	1	2	0	3	2	0
	4	*	0	0	0	0	0	0	2	1	0	1	0	1	0
	5	*	0	0	1	1	1	2	3	1	0	0	1	0	0
	6	*	0	0	0	0	0	0	0	0	2	0	2	1	0
40	1	*	0	0	0	2	1	5	0	0	4	2	1	7	0
	2	*	0	0	1	2	1	1	4	1	2	1	8	3	0
	3	*	2	1	2	3	4	3	5	3	4	2	4	0	0
	4	*	0	0	0	2	1	0	0	1	2	1	3	1	0
	5	*	0	0	2	0	7	3	3	2	3	4	2	0	0
	6	*	0	0	0	0	0	1	1	2	3	0	3	1	0
35	1	*	1	1	2	3	8	3	3	1	8	4	7	4	3
	2	*	1	0	4	1	4	2	3	2	2	1	2	2	0
	3	*	0	1	0	1	1	1	5	3	1	0	4	0	0
	4	*	0	0	3	0	0	1	1	0	0	2	2	1	0
	5	*	1	2	4	4	4	2	4	2	2	5	5	0	0
	6	*	0	0	0	0	0	0	2	0	0	0	0	1	0
30	1	*	3	1	5	10	5	7	4	5	6	4	9	7	1
	2	*	3	3	3	1	8	3	3	1	3	1	7	6	4
	3	*	0	2	2	2	2	1	4	4	7	4	4	0	0
	4	*	0	0	0	0	0	1	2	2	2	2	0	0	0
	5	*	0	3	7	3	4	4	4	3	7	3	3	0	0
	6	*	0	0	0	1	0	0	0	0	0	1	0	1	0
25	1	*	3	2	4	2	6	5	3	4	1	1	5	3	1
	2	*	5	5	4	4	6	3	4	0	3	2	5	3	1
	3	*	0	0	0	1	0	1	3	3	4	1	1	1	0
	4	*	0	0	1	0	0	0	0	1	1	0	1	0	0
	5	*	1	0	3	1	2	2	4	4	1	2	0	0	0
	6	*	0	0	0	0	0	0	0	0	0	0	0	1	0
20	1	*	0	5	6	6	8	2	4	1	5	1	2	1	0
	2	*	0	7	12	9	9	6	3	2	4	2	6	2	0
	3	*	0	0	1	0	5	7	11	5	3	1	1	1	0
	4	*	0	0	0	0	1	3	2	4	7	2	4	0	0
	5	*	0	4	4	3	4	2	6	3	0	3	3	1	0
	6	*	0	0	0	0	0	0	0	1	2	2	1	0	0

CODE FOR CELL SIZE

1 NONE	4 LARGE
2 SMALL	5 MIXED
3 MEDIUM	6 UNDETERMINED

TABLE A-VI

FREQUENCY DISTRIBUTION OF BAND SIZE

TIROS V, AUGUST 15, TO SEPTEMBER 5, 1962

								LONGITUDE(W)						
LAT	BAND	180	175	170	165	160	155	150	145	140	135	130	125	120
50	1 *	0	0	0	0	1	0	1	1	1	1	1	0	0
	2 *	0	0	0	0	0	2	5	1	2	0	0	0	0
	3 *	0	0	0	0	0	0	1	1	1	0	0	0	0
45	1 *	0	0	0	1	3	0	0	3	5	2	5	5	0
	2 *	0	0	0	2	3	3	4	1	2	3	3	1	0
	3 *	0	0	1	1	0	1	2	1	2	0	1	1	0
40	1 *	1	0	3	5	10	11	8	6	13	9	10	10	0
	2 *	0	0	0	3	4	1	3	3	4	1	8	2	0
	3 *	1	1	2	1	0	1	2	0	1	0	3	0	0
35	1 *	1	4	9	6	16	8	14	6	12	9	12	6	3
	2 *	0	0	3	3	1	0	1	1	1	0	5	2	0
	3 *	2	0	1	0	0	1	3	1	0	3	3	0	0
30	1 *	5	8	13	16	16	14	15	12	15	9	13	8	1
	2 *	0	1	1	1	3	1	1	0	3	1	8	6	4
	3 *	1	0	3	0	0	1	1	3	7	5	2	0	0
25	1 *	7	6	11	8	13	11	11	11	5	4	6	5	1
	2 *	2	1	1	0	1	0	2	1	4	1	6	3	1
	3 *	0	0	0	0	0	0	1	0	1	1	0	0	0
20	1 *	0	16	21	17	25	17	22	11	15	5	7	2	0
	2 *	0	0	1	1	1	3	1	1	3	4	7	2	0
	3 *	0	0	1	0	1	0	3	4	3	2	3	1	0

CODE FOR BAND SIZE
1 NONE 2 SMALL 3 LARGE

APPENDIX B

MEAN SYNOPTIC CONDITIONS DURING THE TWO TIME PERIODS

The large scale synoptic features of the eastern north Pacific are dominated by the quasi-stationary pattern of the Pacific Anticyclone during the summer months.

The northern half of the region can be under the influence of the polar front and accompanying migratory anticyclones periodically at this time of the year. The quasi-stationary conditions of the southern half are also interrupted by smaller-scale perturbations in the form of tropical storms moving into the region. Data from TIROS III (Sadler, 1962) and TIROS V (Sadler, 1964) have shown that storms frequently move westward across the eastern north Pacific during the summer, but tend to remain below latitude 20N (the southern boundary for the region used in this study).

The mean position of the polar front can vary over a relatively wide range of latitude from year to year. The variation determines in large part the degree to which the circulation pattern deviates from the long-term mean for a given year. The two time periods used show examples of the types of deviations resulting from this factor.

During the 1961 period the mean position of the polar front in the western half of the region was between 35N and 40N latitude. The effect of this is shown in the mean sea-level pressure pattern in Fig. B-1. The center of the Pacific Anticyclone was located at 37N 144W with a central pressure of 1025 mb. This compares with a long-term mean pressure pattern with a central pressure of 1027 mb located at 48N 149W for the month of

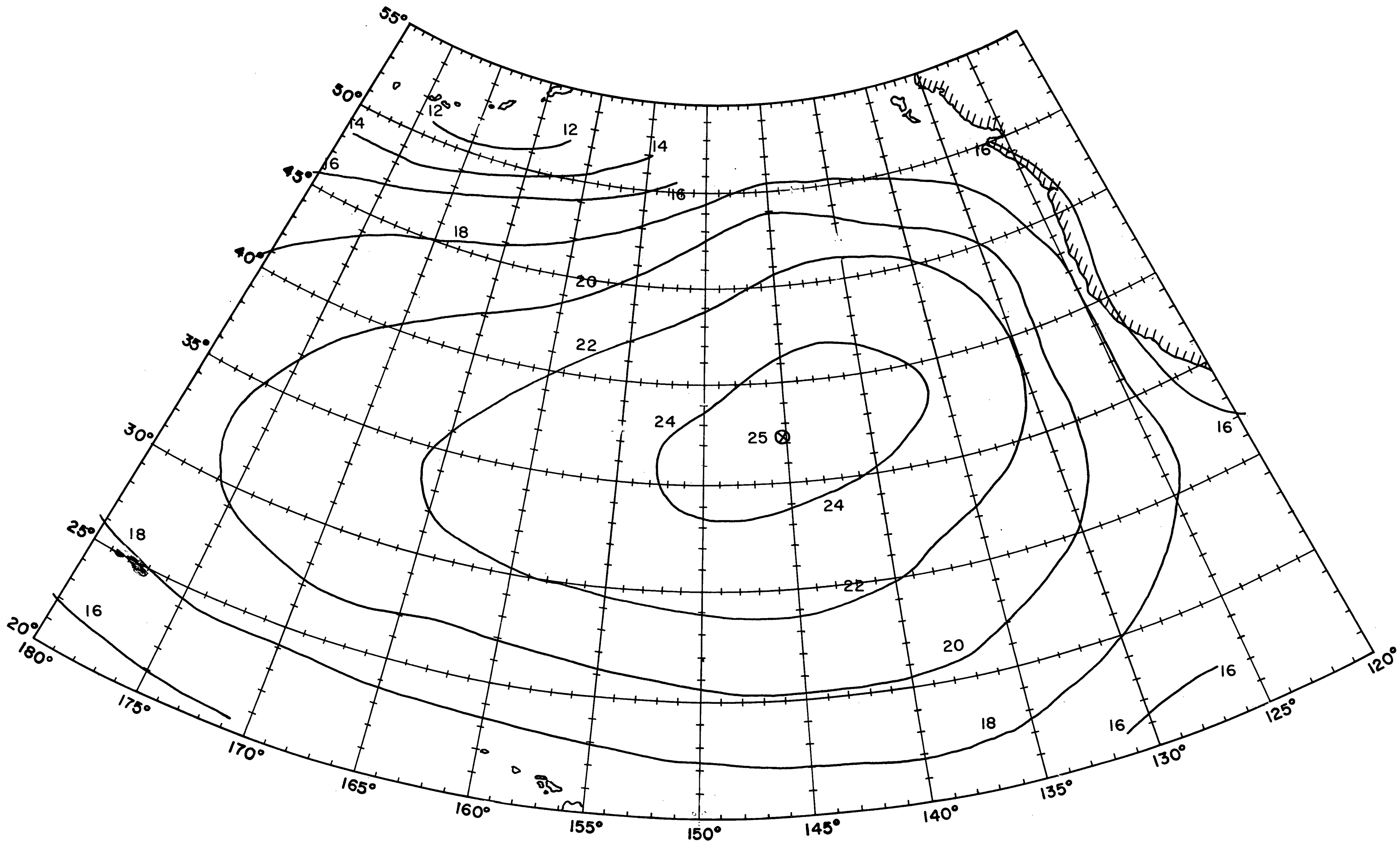

Fig. B-1. Mean sea-level pressure (mb) for the period August 15, to September 5, 1961.

August (Fig. 1). This is 5° longitude west of the mean position of the center for the 1961 period. The deviations from the long-term mean are shown in Fig. B-2. The major deviations are located almost exclusively in the northwest quadrant. With few exceptions this quadrant had a mean sea-level pressure more than two millibars below normal with some portions more than 4 millibars below normal.

The mean sea-level pressure pattern for the 1962 period is shown in Fig. B-3. The central pressure was approximately 1026.5 mb and was located near 41N 153W or about 300 mi northwest of the climatological position. The deviations of the sea-level pressure from the long-term mean are shown in Fig. B-4. Again, as in the 1961 period, the major deviations are located in the northwest quadrant. During the 1962 period, the western portion of the northwest quadrant had mean sea-level pressures as much as three millibars below normal while the eastern portion was about the same amount above normal. The remainder of the region showed a mean sea-level pressure pattern similar to the 1961 period and the long-term mean.

The comparison of the mean sea-level pressure pattern with the climatological pattern for each of the two time periods serves to demonstrate that for this variable, we are dealing with quasi-stationary conditions in three of the four quadrants. It should also be pointed out that it was primarily because of the more southerly location of the polar front during the 1961 period that it took a total of 72 passes of the satellite

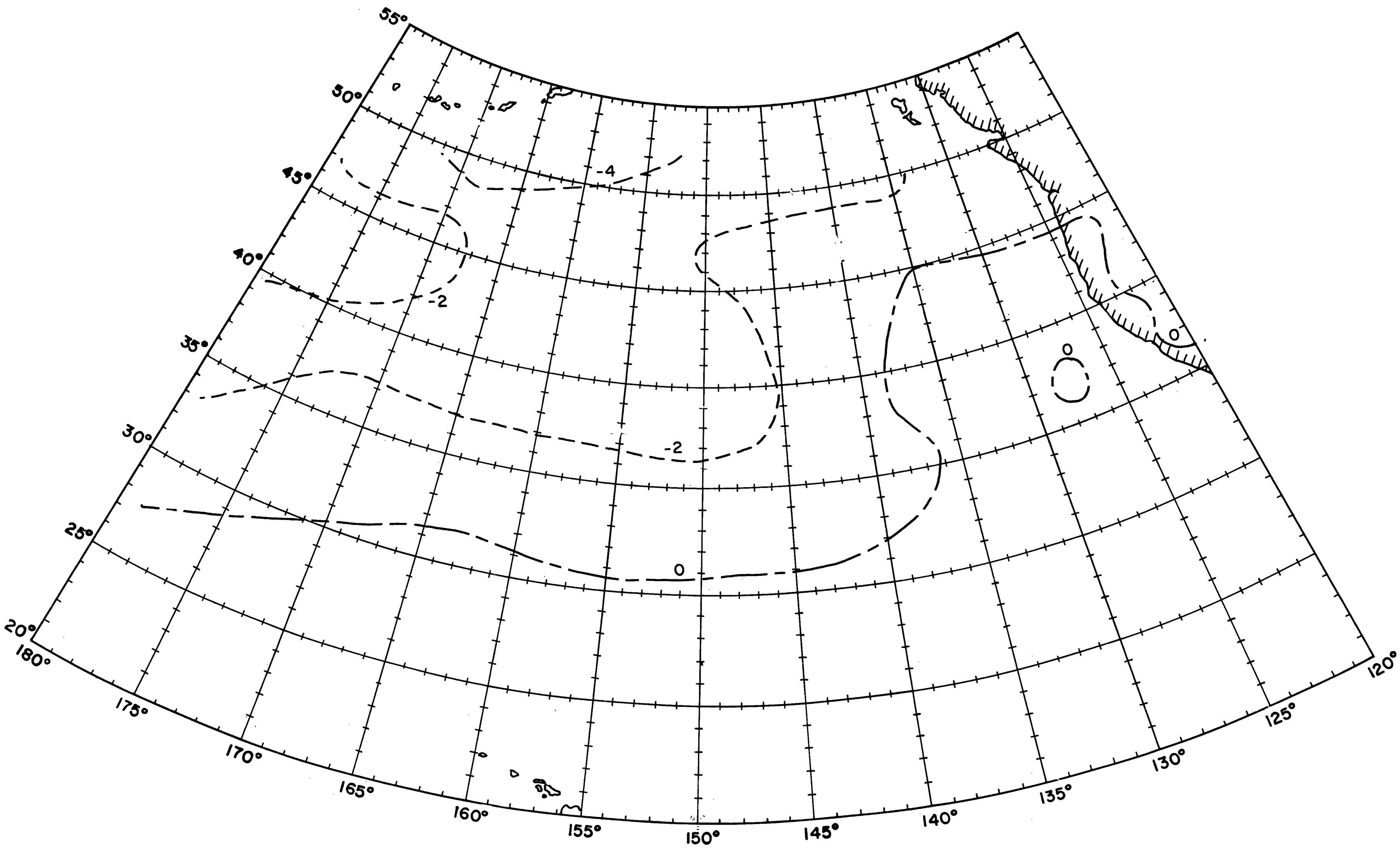

Fig. B-2. Deviations of Fig. B-1 from the mean for the month of August.

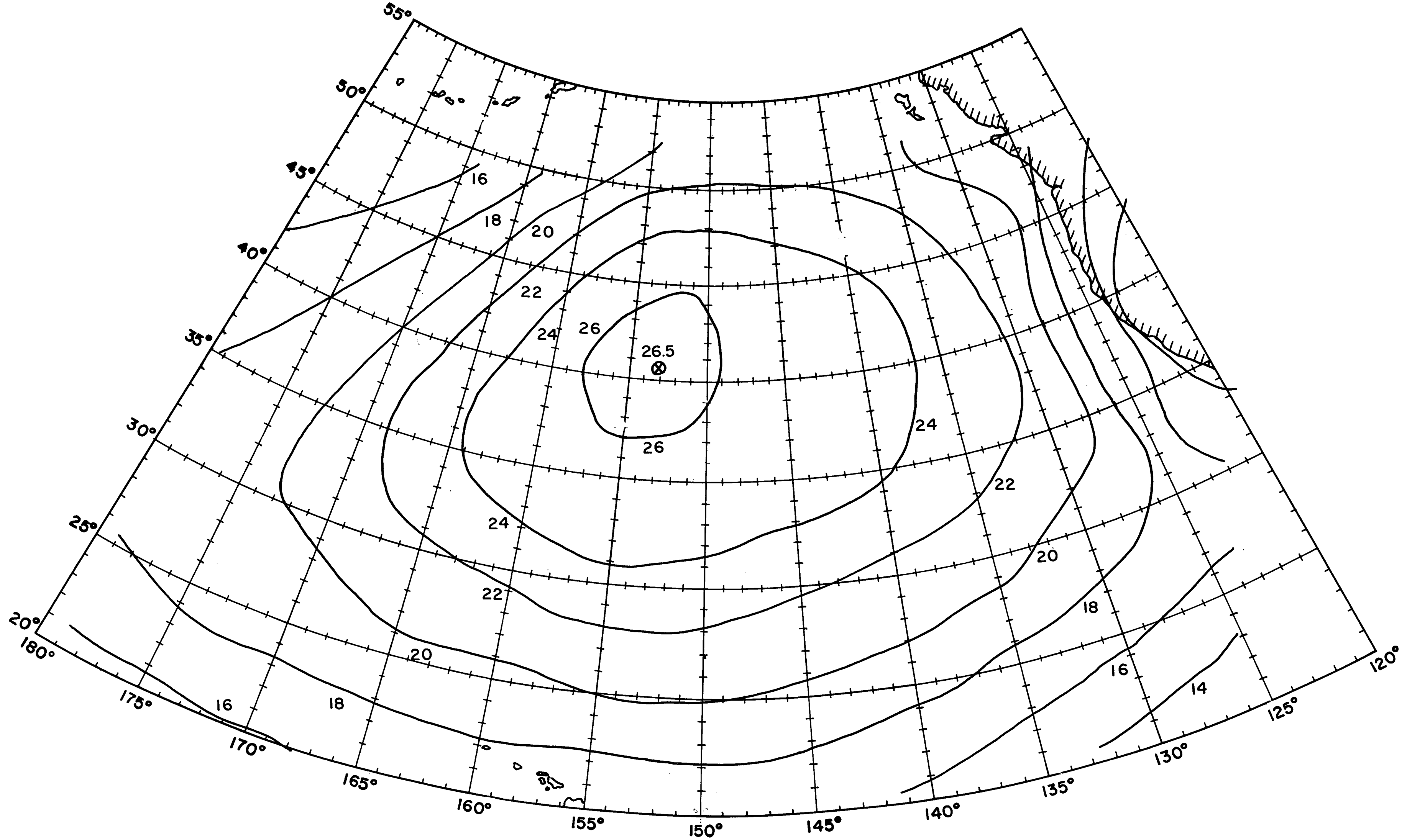

Fig. B-3. Mean sea-level pressure (mb) for the period August 15, to September 5, 1962.

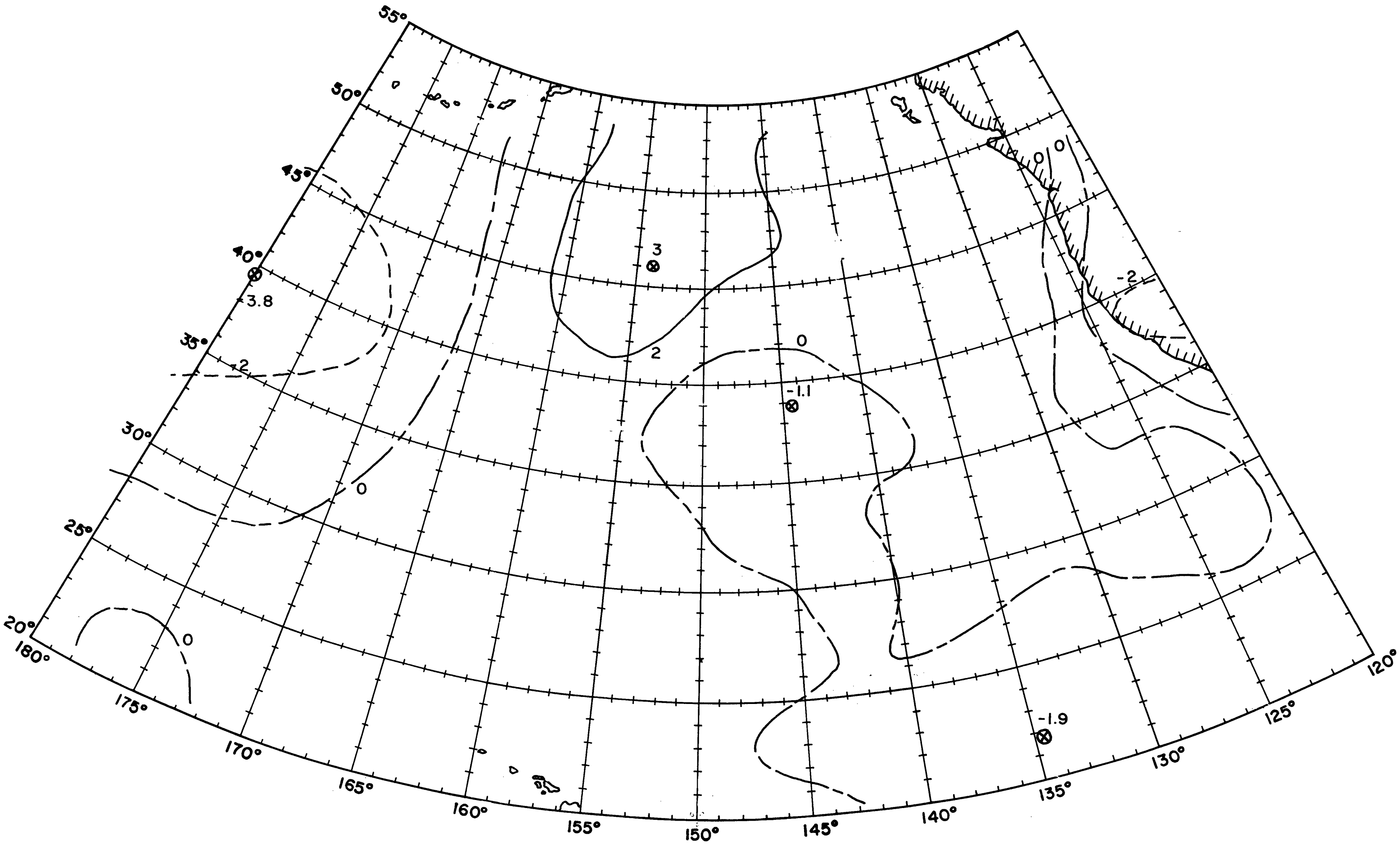

Fig. B-4. Deviations of Fig. B-3 from the mean for the month of August.

to obtain roughly the same amount of cloud observations as was obtained in 42 passes during the 1962 period. Many of the observations for the 1961 period had to be discarded because of their proximity to the polar front.

The effect of the two different types of deviations of the mean sea-level pressure on the circulation around the high pressure area is shown in Figs. B-5 and B-6. Figure B-5 shows the difference in the daily average U-component of the surface geostrophic wind during the 1962 period from that of the 1961 period. The same type of difference for the V-component is shown in Fig. B-6. These are differences in the time mean of the U- and V-components as opposed to differences in the U- and V-components determined from the mean sea-level pressure patterns shown in Figs. B-1 and B-3.

The deviations in the U-component (Fig. B-5) are almost without exception negative over the entire region. This shows a decrease in the westerlies in the northern half of the region and an increase in the easterlies in the southern half. In the northwest quadrant the decrease in the westerlies is as large as 5 m/sec. The same quadrant also shows large deviations in the V-component of the surface wind from the 1961 to the 1962 period (Fig. B-6). A comparison of the same type of deviations in the daily average total wind speed (Fig. B-7) with the deviations in the U- and V-components shows that the change in the northwest quadrant is for the most part a change from a zonal flow in the 1961 period to a more meridional in the 1962 period. By the same comparison the southwest quadrant shows increase in the average wind speed as large a 2 m/sec.

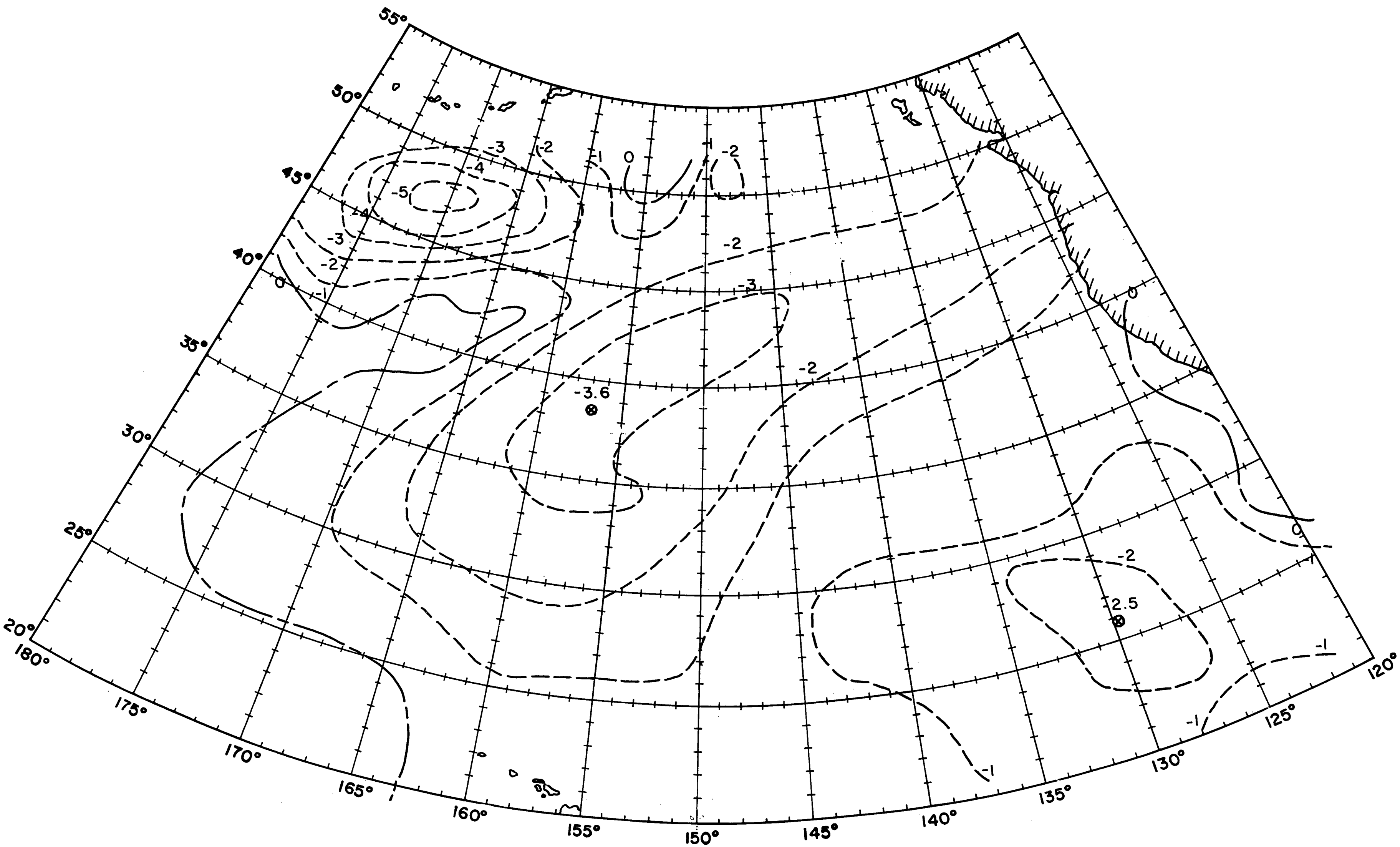

Fig. B-5. Differences in the daily average value of the **U**-component of the surface wind (m/sec) for the two time periods.

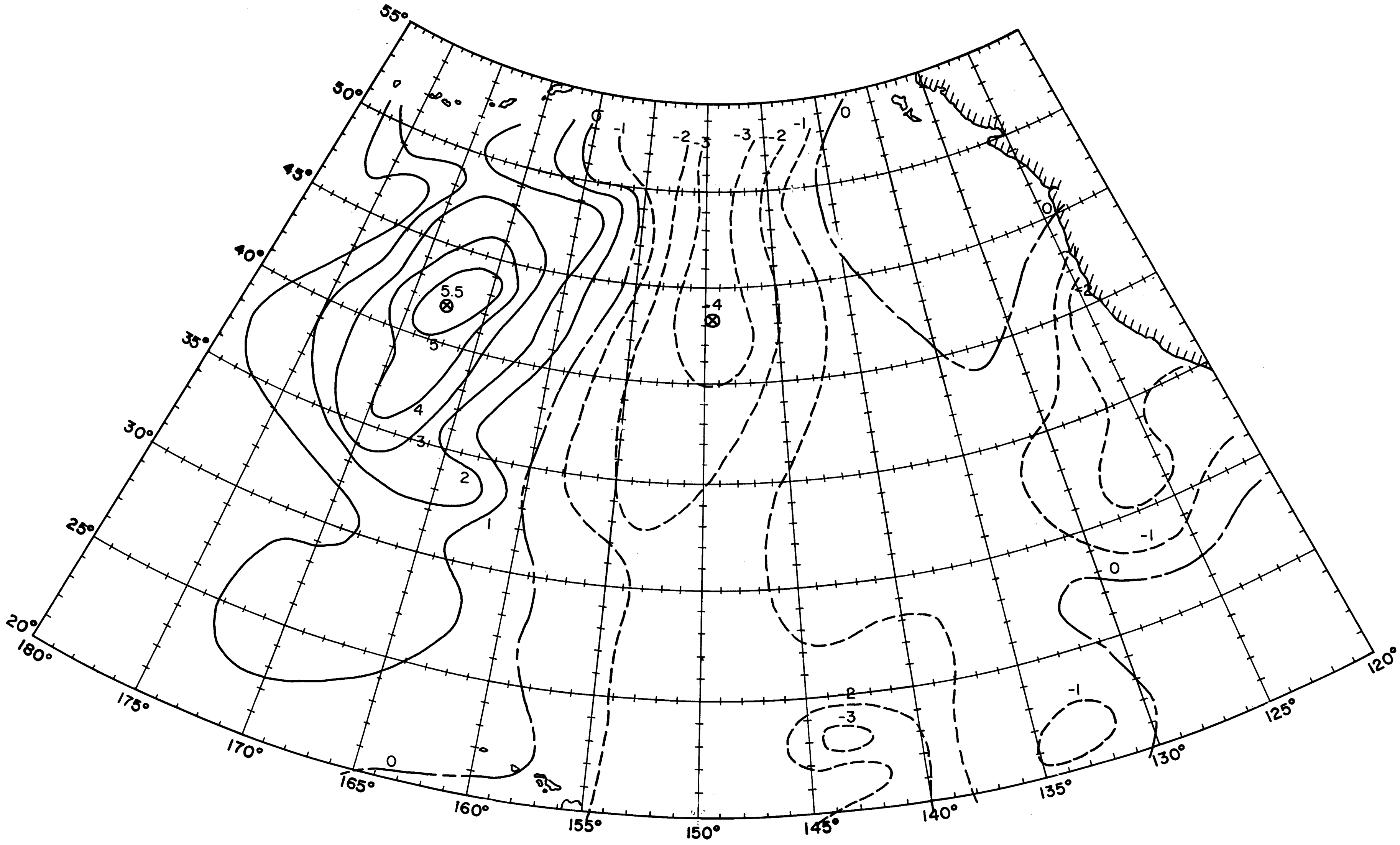

Fig. B-6. Differences in the daily average value of the V-component of the surface wind (m/sec) for the two time periods.

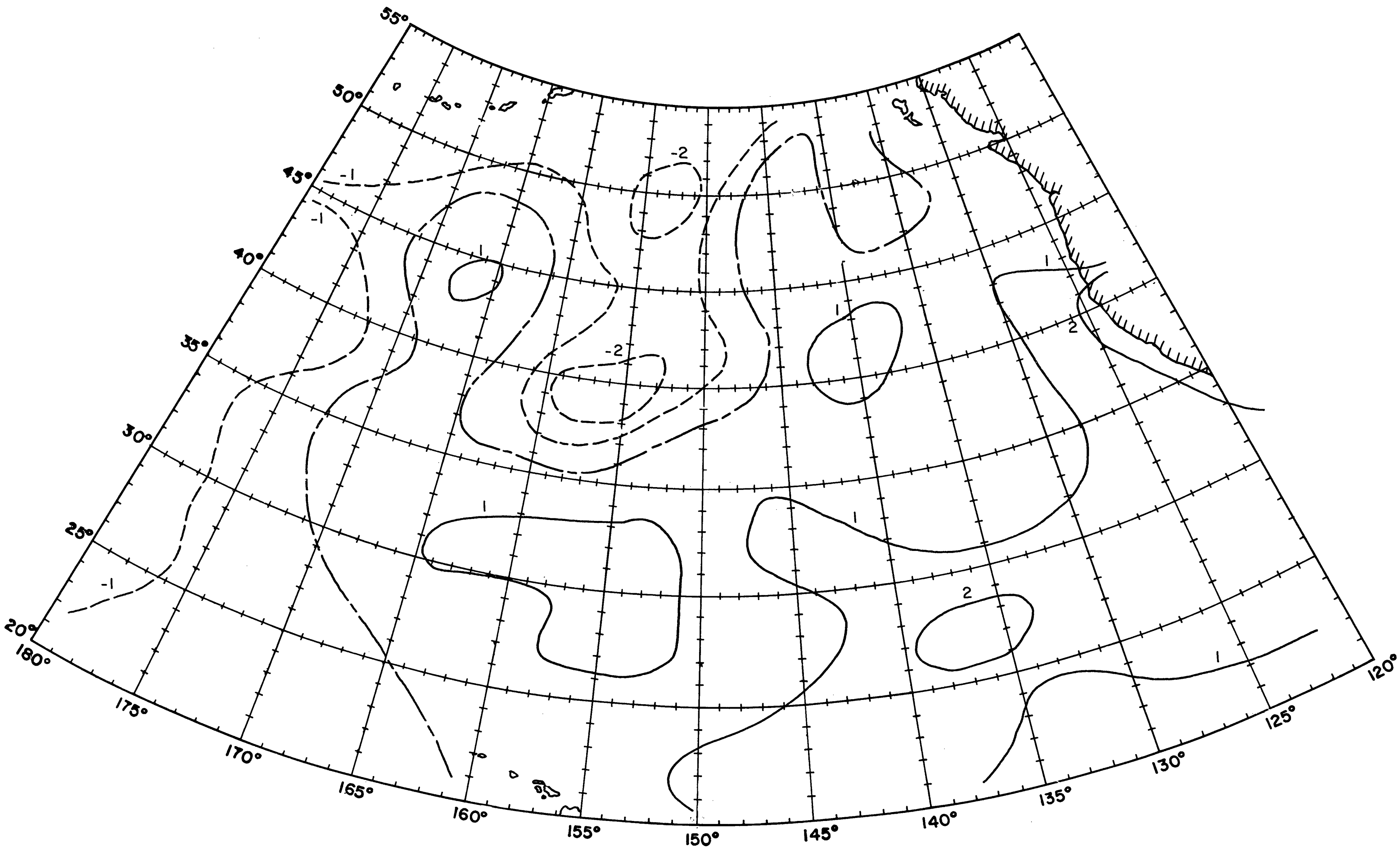

Fig. B-7. Differences in the daily average value of the surface geostrophic wind speed (m/sec) for the two time periods.

The deviations of the surface air temperature from the long-term mean for the most part are reflections of the deviations shown in the sea-level pressure patterns. The temperature deviations for the 1961 period are shown in Fig. B-8. The above normal temperatures in the eastern part of the region result from a flow off the continent as a result of the more easterly location of the Pacific Anticyclone. The below normal temperatures in the northwestern quadrant can be attributed to the cold air advection from the northerly flow of the migratory anticyclones to the north of the polar front.

The temperature deviations for the 1962 period are shown in Fig. B-9. A large portion of the northwest quadrant experienced mean temperatures more than 2°F above the long-term mean. This is primarily the result of the increased and more sustained southerly flow ahead of the polar front.

The deviations of the water temperatures from the long-term mean for the month of August showed different patterns from that shown by the deviations for the surface pressure field and the air temperatures. During the 1961 period (Fig. B-10) the northwestern extremity of the region showed mean water temperatures as much as 4°F below the long-term mean. Almost without exception the remainder of the region showed mean water temperatures above the long-term mean. A major portion of the region was more than 2°F above the long-term mean. For both time periods the large gradient in water temperatures along the North American Coast was effectively smoothed. No claims can be made for any high degree of accuracy

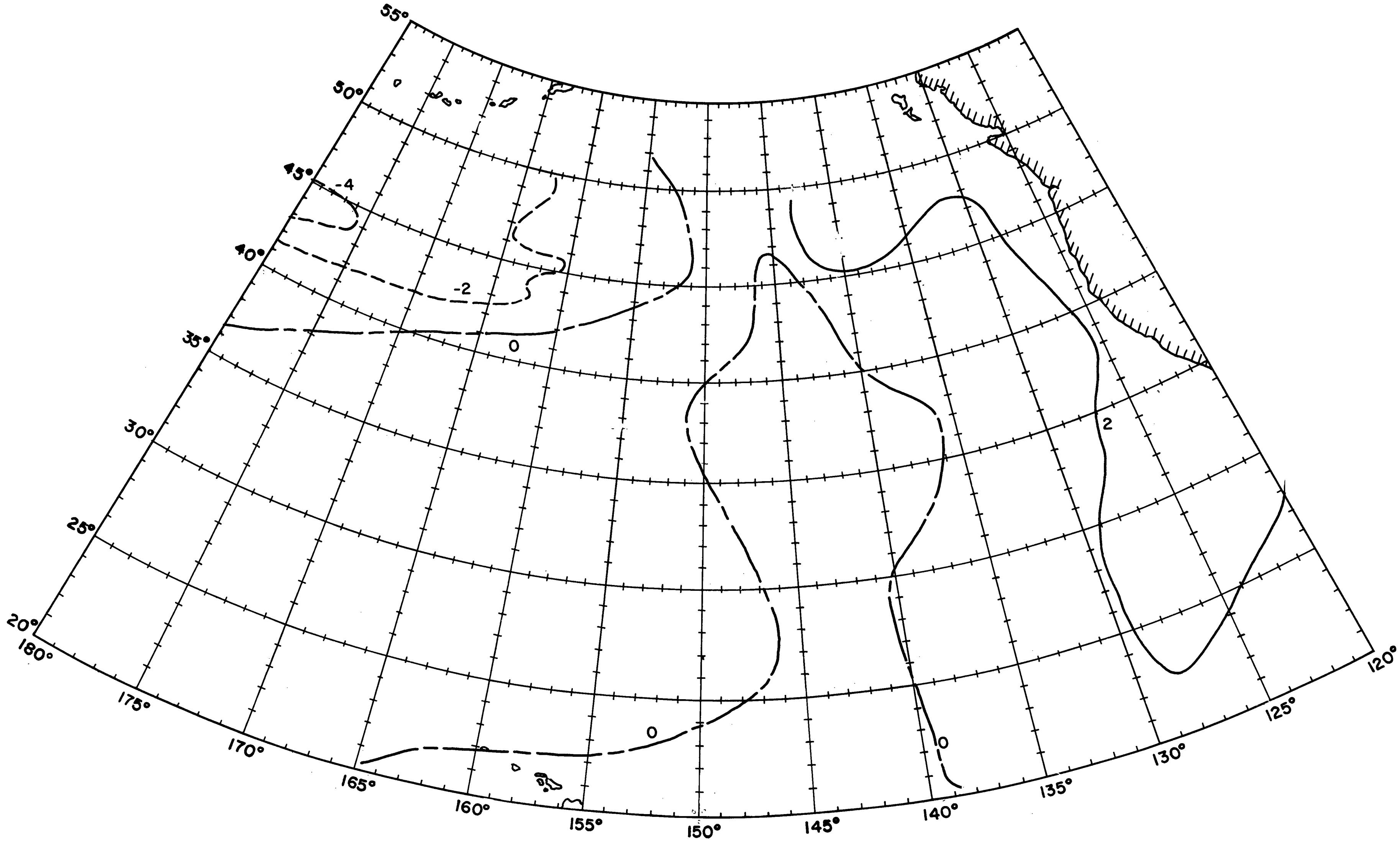

Fig. B-8. Deviations of the average surface temperature of the air (°F) for the 1961 period from the climatological values for the month of August.

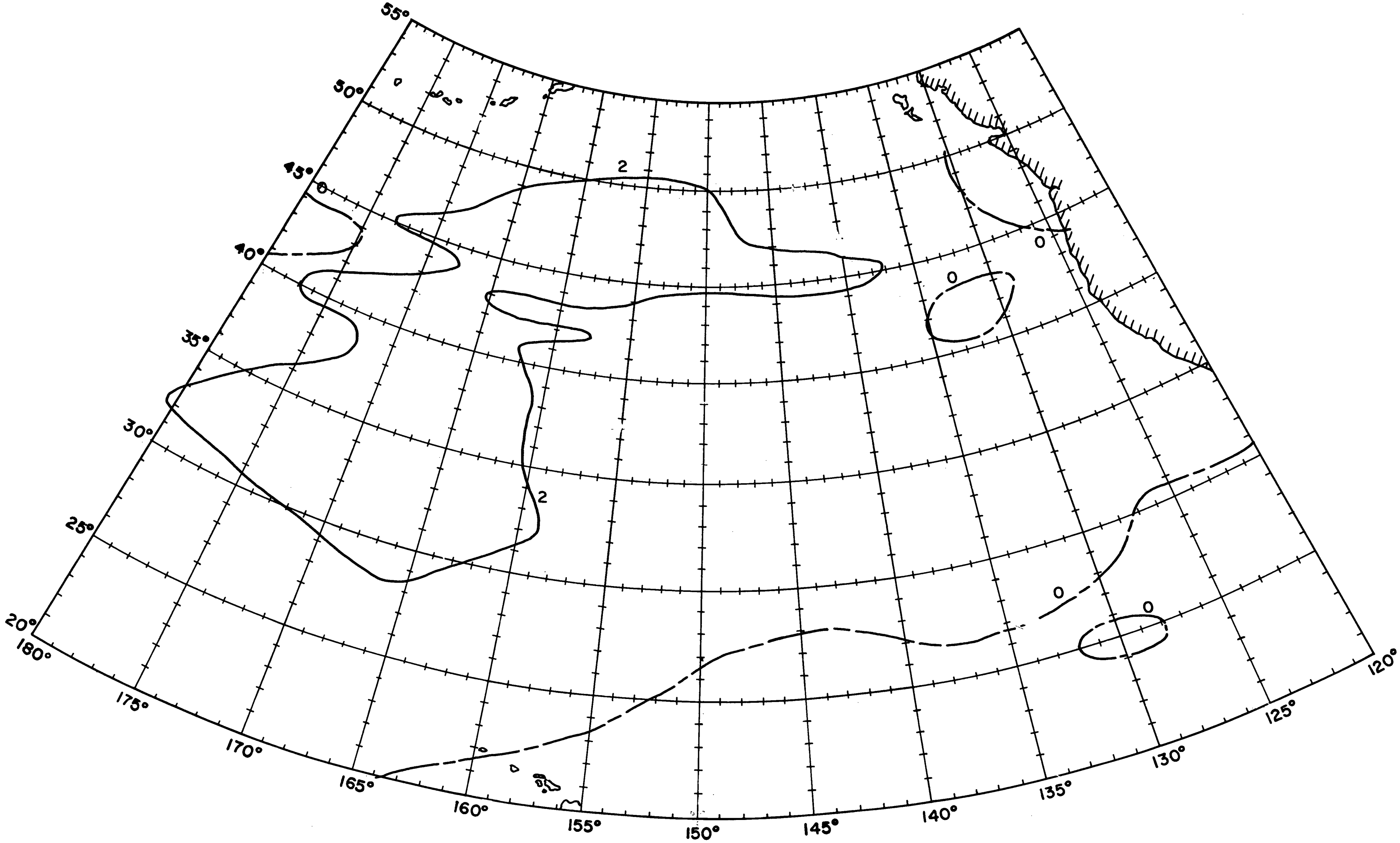

Fig. B-9. Deviations of the average surface temperature of the air (°F) for the 1962 period from the climatological values for the month of August.

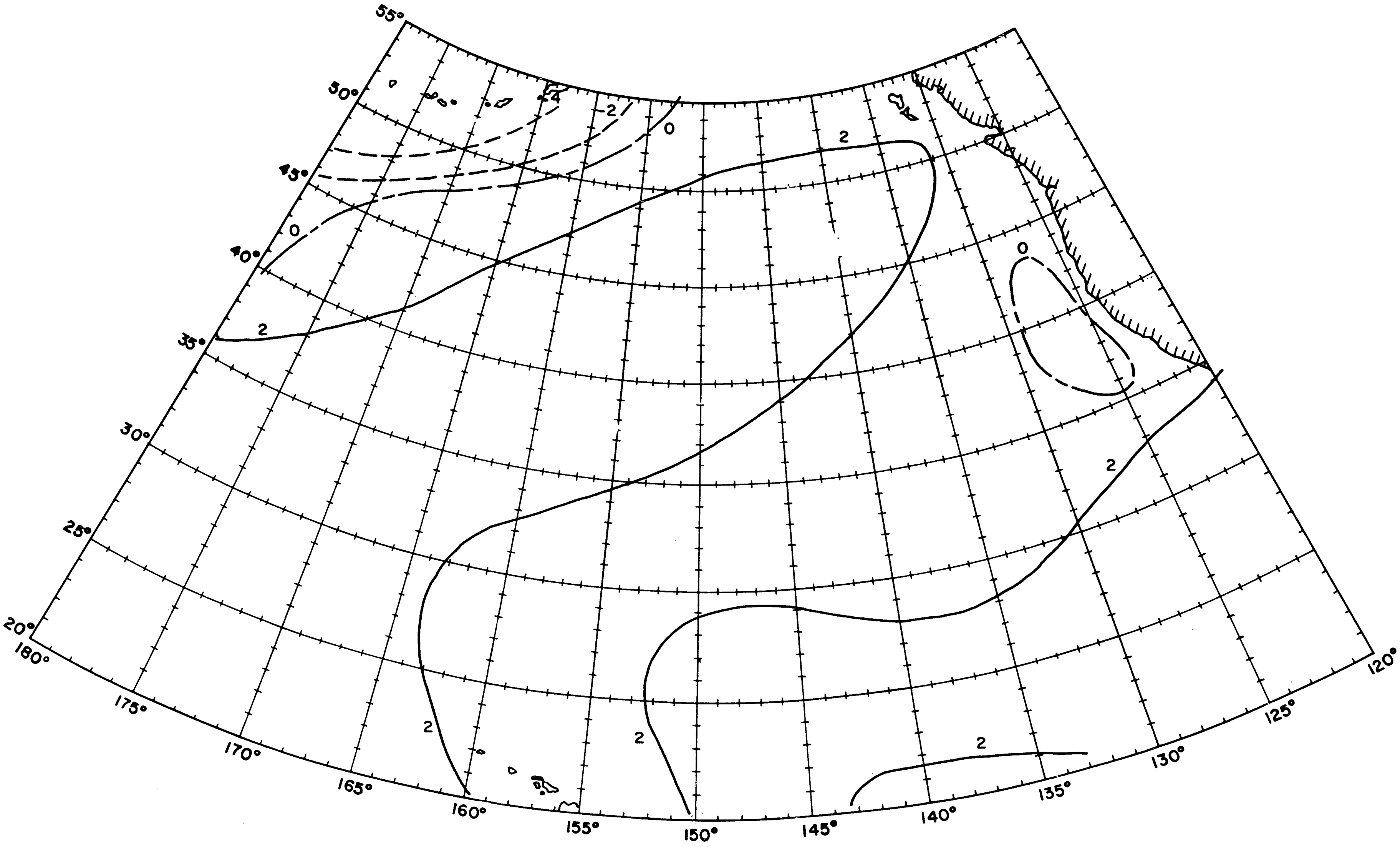

Fig. B-10. Deviations of the average water temperatures (°F) for the 1961 period from the climatological values for the month of August.

in the water temperatures in this region because of the smoothing. Figure B-11 shows that during the 1962 period the entire region, with one minor exception had mean water temperatures more than 4°F above normal. This area of much higher than normal water temperatures has been studied by Namias (1963) in an attempt to establish a relationship between its existence and the abnormal weather patterns experienced over the North American continent during the ensuing fall and winter.

The changes which took place in the synoptic conditions from the 1961 to the 1962 period were largely reflected in the observations of cloud amount. The distribution in the northwest quadrant showed a shift toward more frequent occurrences of fewer clouds during the 1962 period. The other three quadrants showed practically no changes in the distribution during the second year. The changes in the distribution of observations of cell size, if any, during the second year cannot be determined due to the induced bias toward the groups with small cells.

The changes which took place in the variable of cloud bands was not only in the frequency but also in the preferred location of occurrence. The 5° latitude and longitude "squares"—which experienced large changes in the frequency of occurrence during the 1962 period are shown by the different hatching in Fig. B-12.

The synoptic variables whose changes from one year to the next most nearly matched those of the cloud banding were TWS (Fig. B-13) and SNH (Fig. B-14). Z85 was computed only for the positions where cloud observations were available.

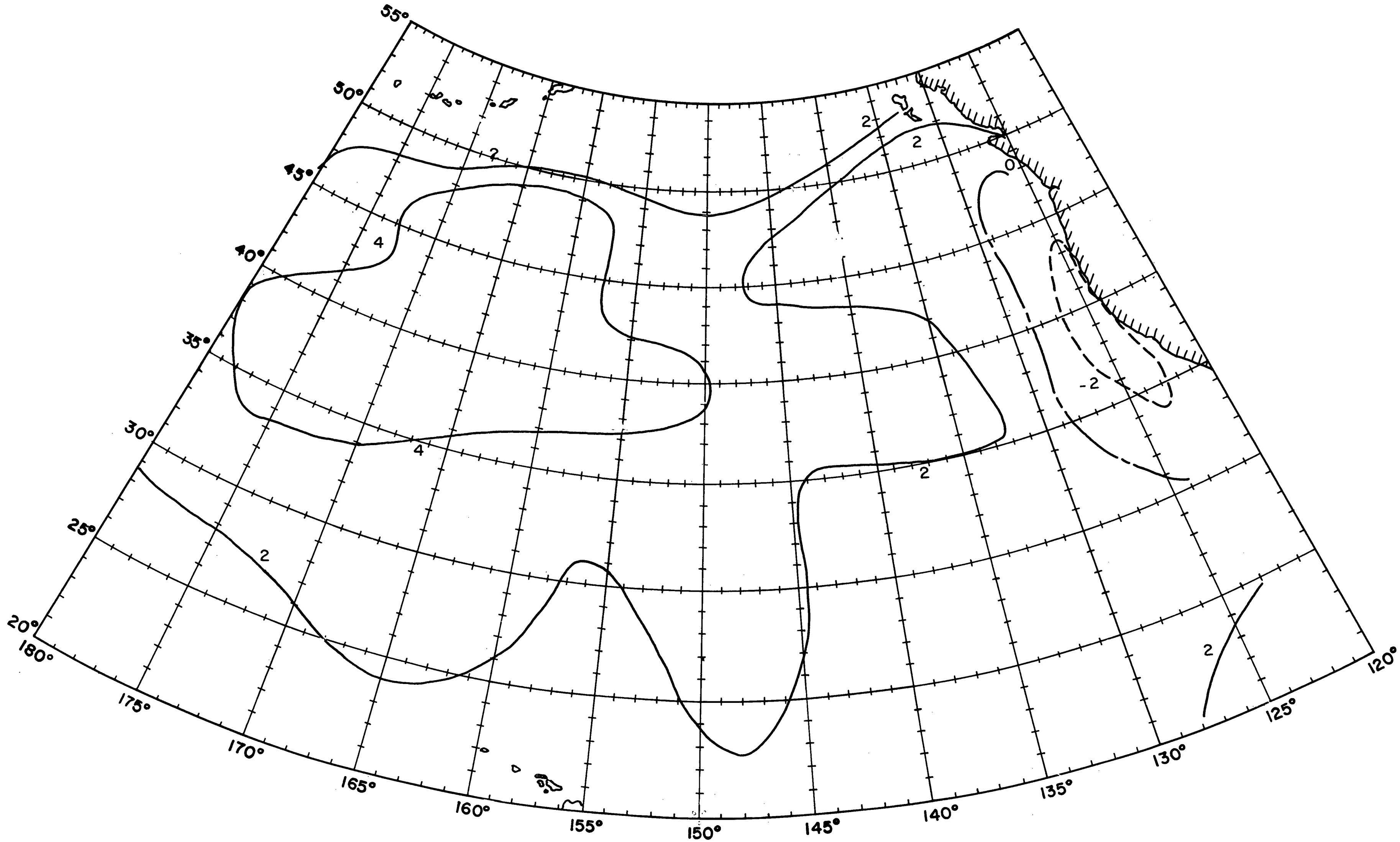

Fig. B-11. Deviations of the average water temperatures (°F) for the 1962 period from the climatological values for the month of August.

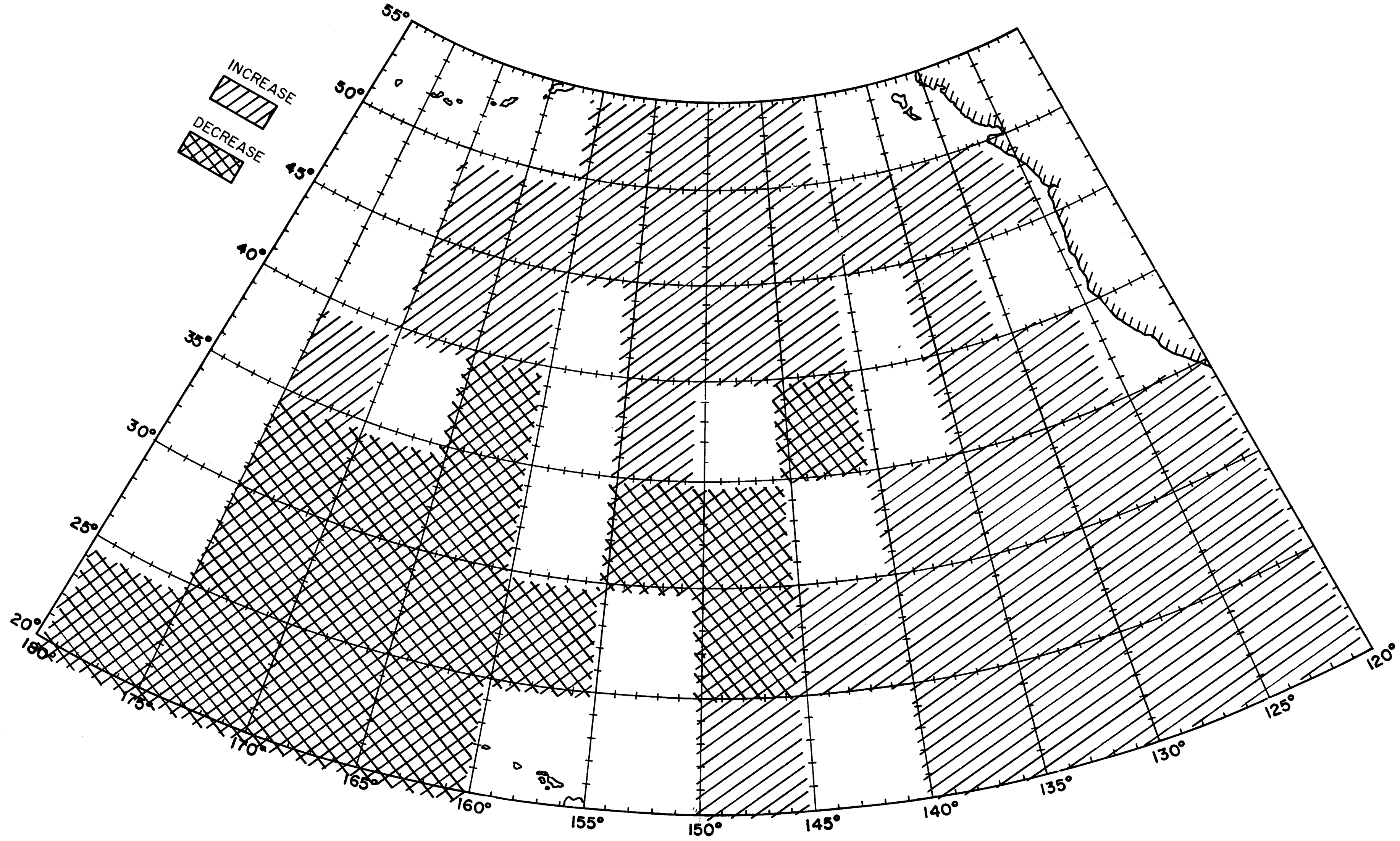

Fig. B-12. Areas which had significant changes in the frequency of occurrence of cloud bands for the 1962 period over that which occurred during 1961.

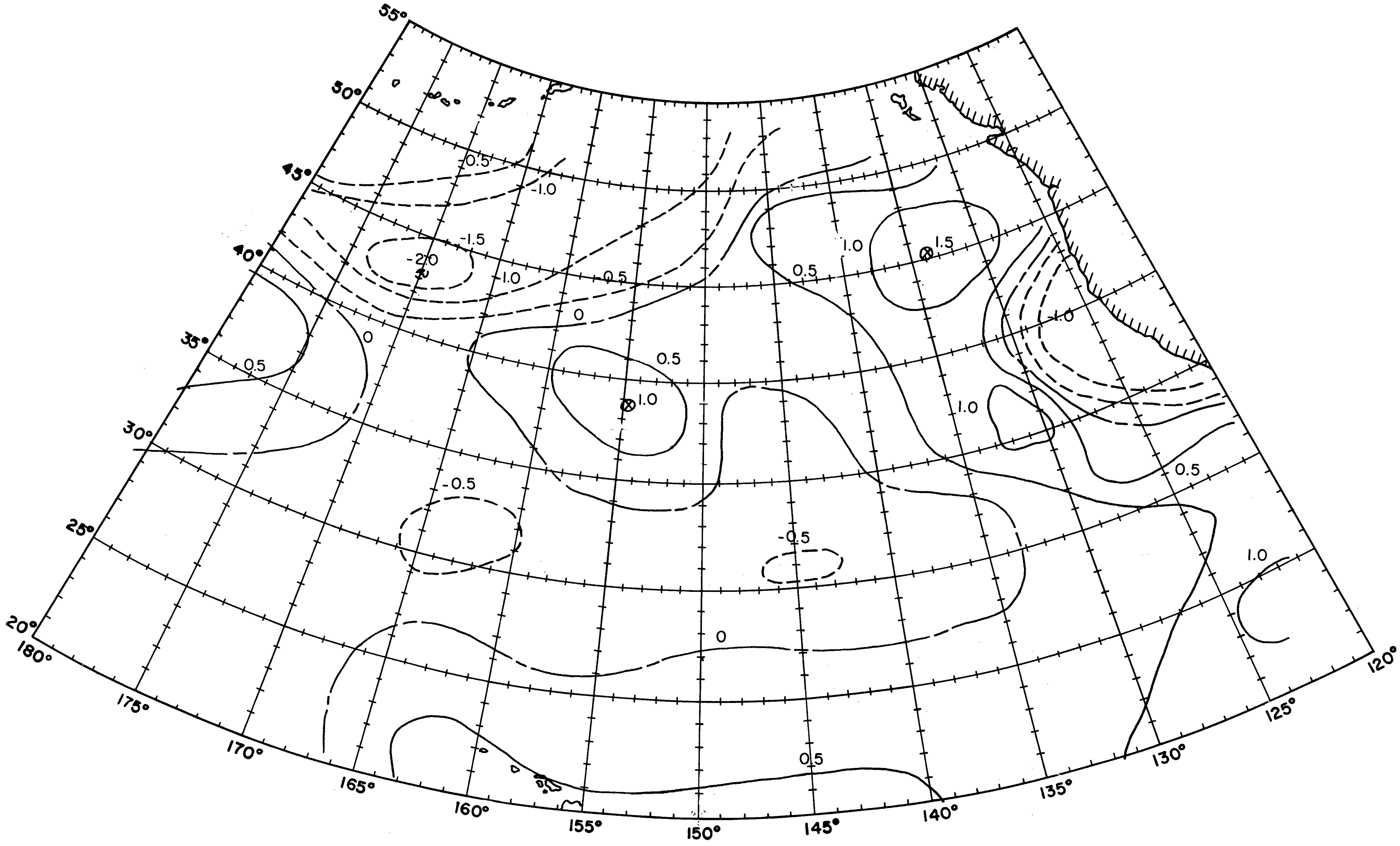

Fig. B-13. Changes in the average values of the water-air temperature differences (°F) from the 1961 to the 1962 period.

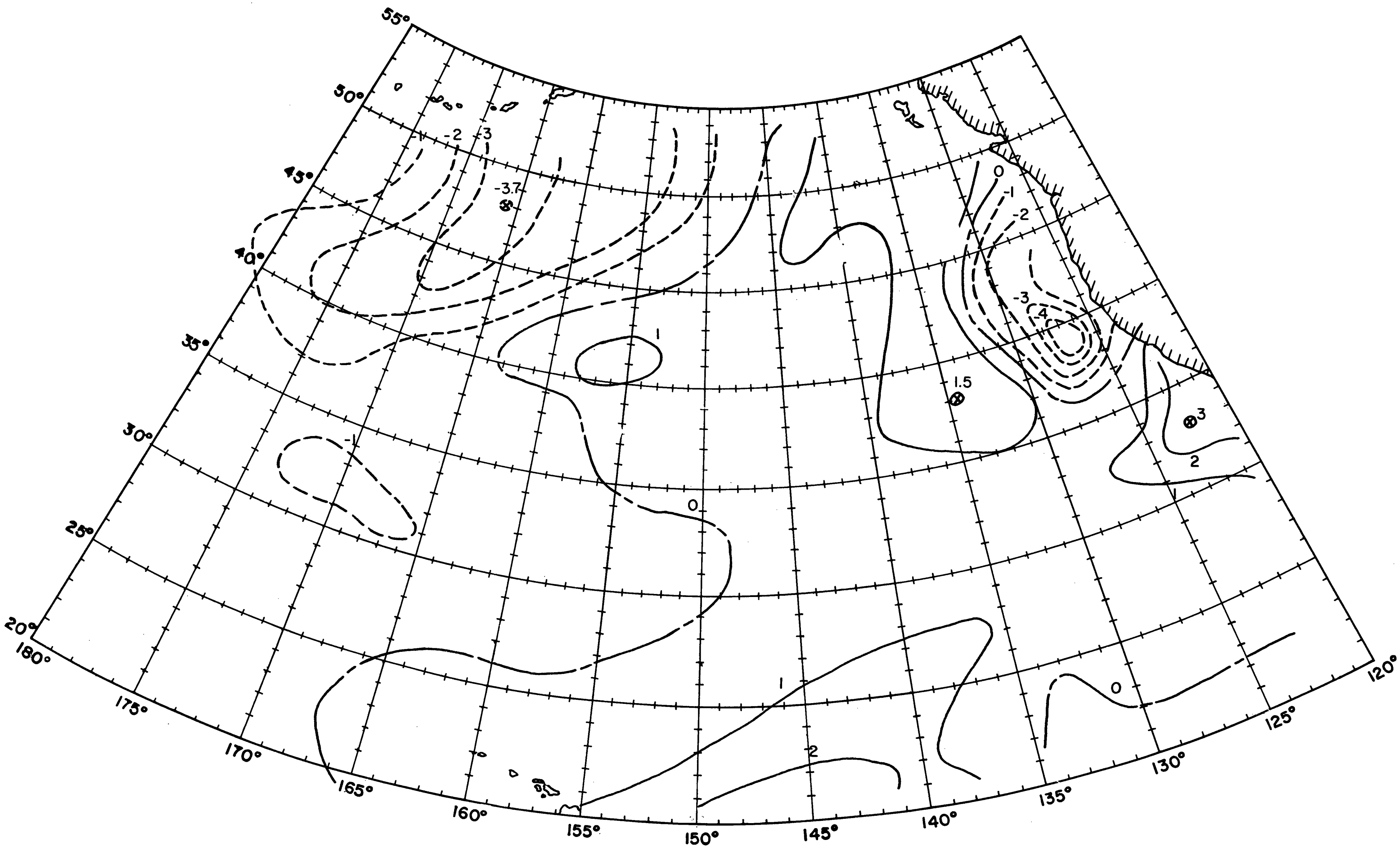

Fig. B-14. Changes in the average values of the sensible heat transfer (cal m^{-2} sec^{-1}) from the 1961 to the 1962 period.

The synoptic variable DTN showed significant changes in the mean pattern from the first year to the second. The mean obtained as an average of the 22 values for DTN in 1961 is shown in Fig. B-15. Those for the 1962 period are presented in Fig. B-16. The changes which took place from one period to the next are shown in Fig. B-17.

The increase in the frequency of occurrence of cloud bands in the northern half of the region can be associated with a decrease in DTN. The increase in the southeast quadrant on the other hand is just as definitely associated with an increase in DTN. If DTN is at all associated with cloud bands then a further distinction in type must be made from that used in this study. Perhaps the orientation of the bands with respect to the wind would yield more information than their spacing.

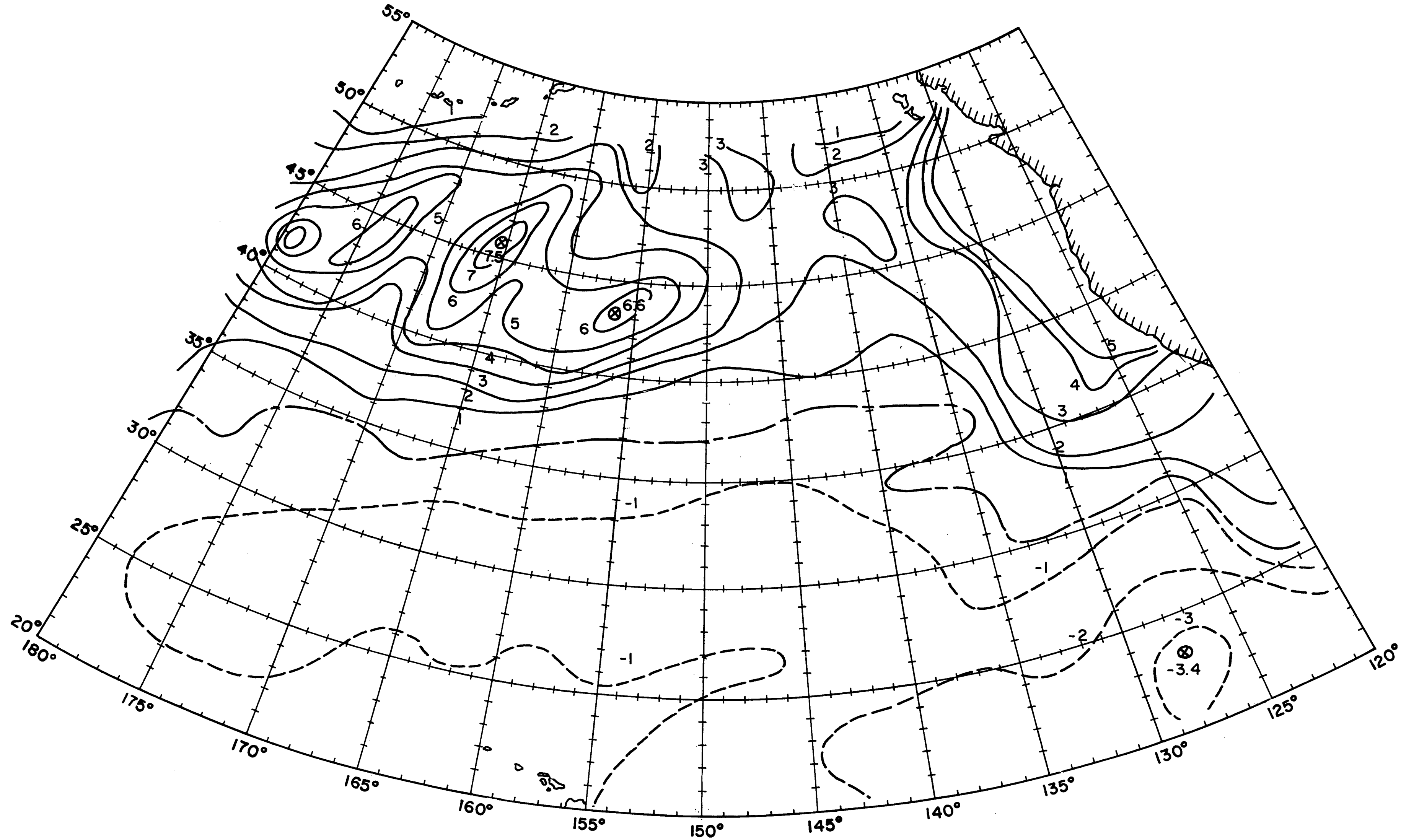

Fig. B-15. Daily average value of the thermal gradient normal to the surface wind for the 1961 period (10^{-2}°C/km).

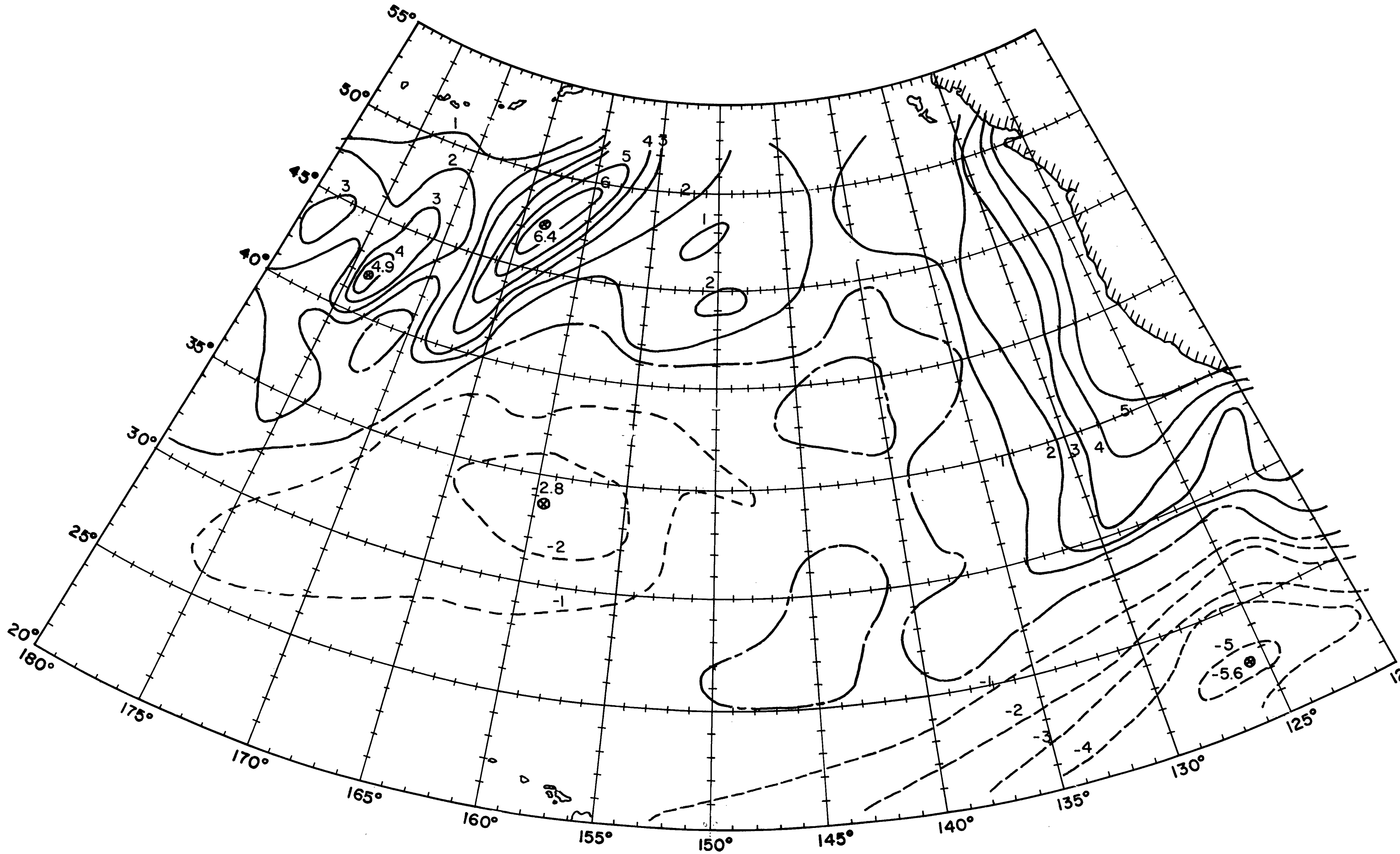

Fig. B-16. Daily average value of the thermal gradient normal to the surface wind for the 1962 period (10^{-2}°C/km).

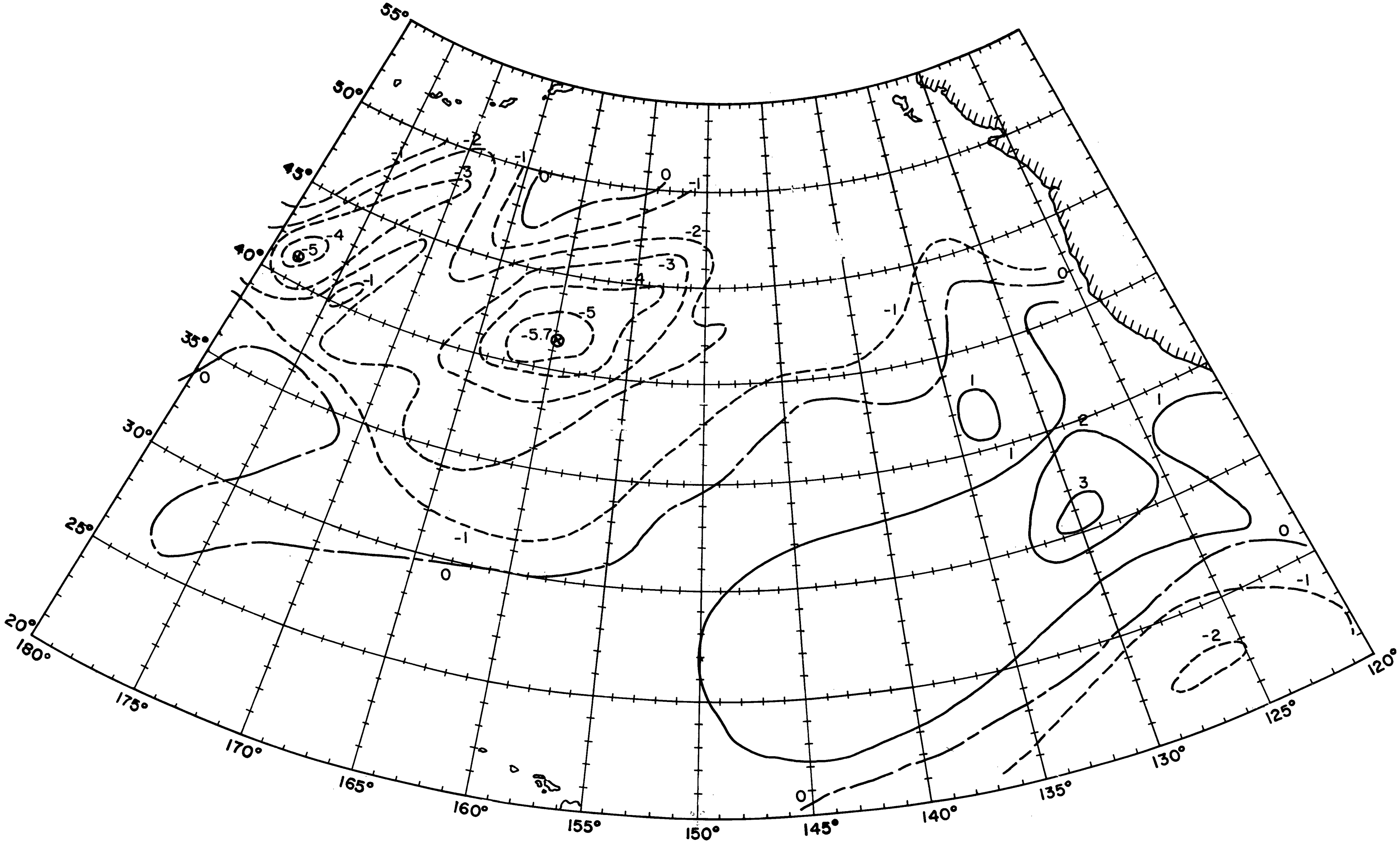

Fig. B-17. Changes in the daily average value of the thermal gradient normal to the surface wind (10^{-2}°C/km) from the 1961 to the 1962 period.

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