THE CLIMATOLOGY AND NATURE OF TROPICAL CYCLONES OF THE EASTERN NORTH PACIFIC OCEAN

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THESIS

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ABSTRACT

Meteorological satellites have revealed the need for a major revision of existing climatology of tropical cyclones in the Eastern North Pacific Ocean. The years of reasonably good satellite coverage from 1965 through 1971 provide the data base from which climatologies of frequency, duration, intensity, areas of formation and dissipation and track and speed characteristics are compiled. The climatology of recurving tracks is treated independently.

The probable structure of tropical cyclones is reviewed and applied to this region. Application of these climatologies to forecasting problems is illustrated. The factors best related to formation and dissipation in this area are shown to be sea-surface temperature and vertical wind shear. The cyclones are found to be smaller and weaker than those of the western Pacific and Atlantic oceans.

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I. INTRODUCTION AND OBJECTIVES OF THE STUDY

Interest in tropical meteorology was spurred by the introduction of operational weather satellites in 1964. It soon became apparent that the frequency of tropical-cyclone occurrence off the Pacific coast of Mexico was greater than apparent from records of known storms in the years 1945 through 1963. Since 1964 there is reasonable confidence that all the significant tropical storms and hurricanes have been detected and tracked with the assistance of weather satellites and, to a lesser extent, military aircraft reconnaissance. Fleet Weather Central(now Fleet Weather Facility), Alameda, California has routinely co-ordinated with the National Weather Service Forecast Office in Redwood City, California in the issuance of tropical cyclone warnings.

Tropical cyclones are highly individual in their behavior, yet there are shared similarities which can be used to present a meaningful description of normal behavior. The variations observed are partly a product of real differences and partly the result of infrequent and uncertain observations taken under the most trying of circumstances. In typical weather reports a ship's actual distance and bearing from the cyclone eye were seldom given, nor could they be determined on the basis of analysis since there were not enough other reports to fix the storm location. In general, the sparseness of reports made it difficult to determine a typical wind field or to locate a cyclone with any accuracy

in the 1950's and early 1960's. In some instances military aircraft reconnaissance was made to determine the location and intensity of a disturbance as a supplement to surface data.

The primary aid to the mariner in avoiding severe weather near the core of intense tropical cyclones is foreknowledge of the existence and intensity and anticipated changes in intensity and movement of these systems. This information is the substance and responsibility of marine weather analysis and forecasting. In the present state of the art, tropical cyclones cannot long evade detection by weather satellites. These systems are now detected at an earlier stage and with greater accuracy of position than ever before possible. Thus, the skills of the meteorologist can be diverted from the task of location and applied to the problems of description of weather elements about the cyclone and the forecasting of its movement and evolution.

The natural consequence of earlier detection and more accurate tropical cyclone warnings is that fewer ships are now caught within the circulation of severe tropical cyclones. The operating meteorologist has, for this reason, lost many of the surface reports that in earlier years would have proven the existence and intensity of tropical cyclones. It has become necessary to place increasing reliance on models developed from historical records and current research to infer the nature of the tropical cyclone from meteorological satellite data.

It is the feeling of the author that a sufficiently complete and extensive data base can be compiled at this time to construct a comprehensive climatology pertaining to tropical cyclones in the eastern North Pacific Ocean. The construction of such a climatology is an immediate objective of this study. It would be of immediate operational use in forecasting and additionally might serve to delineate areas of future research which are peculiar to the region or are well exemplified within the region. In particular the processes of tropical cyclogenesis and dissipation will be examined on the basis of the climatologies developed or assembled from a thorough research of recent literature.

Objectives of this study, as they relate to the eastern tropical North Pacific Ocean area, follow:

1. To research recent scientific literature and compile a complete bibliography of articles pertaining to the climatology and modeling of tropical cyclones.
2. To research and assemble a comprehensive tropical-cyclone data base.
3. To construct an operationally-oriented climatology of tropical cyclones for use in improving analysis and marine forecasts, particularly as they apply to Optimum-Track Ship Routing (OTSR).
4. To study the processes of formation and dissipation of tropical cyclones.
5. To study aspects of 1970 tropical cyclones as they relate to the above objectives.

II. THE AREA OF STUDY: NATURE OF THE PROBLEM

The eastern tropical North Pacific Ocean (EASTROPAC) as used in this study extends from the west coast of Mexico and Central America to 140W in the area south of 30N. Seldom does a tropical cyclone move westward or northward out of this data-sparse region.

The importance of EASTROPAC to the Navy can be seen from Figure 1 which shows the major sea lanes from the Panama Canal to Hawaii and west-coast United States ports. As much as thirty percent of all Pacific OTSR forecasts by FNWC involve passage through this region and require forecasts or outlooks extending from one day to one month in duration. Freeman (1972) tabulated 585 Navy or Navy contract-vessel EASTROPAC transits during 1970. The need for an operational climatology of the area is based largely on the requirements of OTSR; however, it would also provide valuable assistance for all meteorologists concerned with day-to-day forecasting of tropical cyclones in this region.

Figure 1 also shows the surface and upper-air data coverage for land stations. When tropical depressions have been identified, aircraft reconnaissance is scheduled. The great distance from home base in California has limited reconnaissance to one daylight fix per day, normally made near 1800 GMT, coinciding with the time of maximum ship coverage and close to the time of a satellite observation. This combination of circumstances is very likely to produce one

good-quality cyclone-center fix per day followed by 18 hours of extropolation. Poor LORAN conditions sometimes limit aircraft navigation accuracy. EASTROPAC reconnaissance aircraft have sometimes estimated their navigational accuracy to be as low as 20 n mi, which is two to three times the mean value reported for western Pacific aircraft center-fixes by FWC Guam Annual Typhoon Report (1971). Night-time infrared satellite observations, although generally less accurate than the daylight penetration aircraft fix, can be used to locate and monitor the development of cyclones between aircraft fixes.

Ship reports represent the oldest form of locating tropical cyclones. Figure 2 shows the locations of gale force winds encountered by ships in the ten-year period 1962-1971 as compiled from issues of the Mariners Weather Log. Wilgus (1958) reported "the general basis for determining the existence of a tropical storm was one or more reports from vessels experiencing winds of 34 knots or more." Many of these ships were part of the "tuna fleet" working in portions of the tropical-cyclone genesis region during the storm season. The distribution of transient ship reports is observed to follow established sea lanes resulting in vast areas of no reports and occasional high-report densities near shore where land stations are already adequate for synoptic-scale surface analysis. The number and distribution of transient ships in EASTROPAC can be estimated from Freeman (op. cit.) who quoted statistics indicating that 38 ships per day transited the Panama Canal in 1970. A few ships follow Southern Hemisphere

routes, but over 90 percent are estimated to follow the trade routes to the Fast East, Hawaii, or the United States, exiting the EASTROPAC area in six to ten days. If the mean time in the area is taken as eight days, a transient ship population of about 280 vessels is implied. The many ships of the tuna fishing fleet from San Diego and a few coastal steamers and cruise ships that ply these waters increase the total to about 300 ships capable of reporting weather in the area. This estimate is considered to be conservative for any given time and does not include seasonal variations in shipping density. If even a simple majority of these ships reported weather regularly, analysis would be greatly improved. Rather than improving, the situation seems to be deteriorating. Wolff (1970) reports a 25 percent decrease in recent years in the total number of ship weather reports received which he credits to economy measures resulting in reduction of radio services at sea.

Sample days of Tuesday 6 October and Wednesday 7 October, 1970 produced 42 and 44 different ships, respectively, plotted on the operational charts of FWF Alameda and the final National Meteorological Center (NMC) analyses. Hurricane Patricia was then active so maximum cooperation might be expected from transiting ships. The percentage of responding ships in an active hurricane situation was, by these estimations, approximately 14 percent. This agrees reasonably well with an unpublished study by the author in 1965, estimating 11 percent of all transiting ships reporting weather over the

North Pacific Ocean as a whole. Applied to individual charts of 6 and 7 October there was a maximum of 24 reports on any one chart. The 1800 GMT chart has the best coverage and the 0000 GMT chart the next best. EASTROPAC ships that report weather do so while radio operators are commonly on duty, generally during daylight hours.

The density of upper-air reports is totally inadequate to ensure accurate regional analysis. The dependence of Fleet Numerical Weather Central's (FNWC) upper-air analysis on climatology in this region is almost total. Manual modifications of numerical surface and upper-air analyses to correspond with the atmospheric structure implied by satellite data are necessary to achieve good quality analyses and prognoses in this area. Thus, synoptic modeling and climatology are the foundations of EASTROPAC analysis and forecasting.

In order to apply these methods to the specific problem of EASTROPAC cyclone analysis and forecasting, a model of EASTROPAC cyclones must be described and a climatology of EASTROPAC cyclone behavior must be constructed. Finally, rules for applying the model and the climatology to the operational forecast problem must be formulated.

III. DATA SOURCES AND PROCESSING

A. SOURCES

The first complete records of known tropical cyclones in EASTROPAC began in 1945. No published sources of these records for the years 1945 through 1955 were found for this study. Partial records for these and earlier cyclones dating back to 1921 were obtained from the National Weather Service Forecast Office in Redwood City, California. Beginning with the 1956 season, summaries of tropical cyclones in the eastern North Pacific were published annually in the March issue of *Mariners Weather Log*. Beginning with the 1965 season, EASTROPAC tropical-cyclone summaries were prepared by Fleet Weather Central (FWC), Alameda, California and included as Annex A to the *Annual Typhoon Report*, as published by Fleet Weather Central/Joint Typhoon Warning Center, Guam. Operational surface weather analyses and all communications from weather reconnaissance aircraft and satellite pictures for the 1970 season were obtained from FWC, Alameda.

Each issue of the *Mariners Weather Log* features "Rough Weather Log," listing selected weather reports received from ships reporting gale-force winds. Many such reports are recevied by mail and are usable only for climatology or case studies.

Synoptic 200-mb and sea-surface temperature analyses were obtained from FNWC. Monthly sea-surface temperature analyses for 1970 were obtained from the *California Fishery Market*

News monthly summaries published by The United States Department of the Interior, Fish and Wildlife Service, Bureau of Commercial Fisheries, Fishery-Oceanography Center, La Jolla, California. OTSR records for the 1970 season were obtained from FNWC Monterey.

B. PROCESSING

Only tropical storms and hurricanes were used in compiling EASTROPAC statistics. A statistical study of points of origin was restricted to the years of good satellite coverage, beginning in 1964. Studies of recurving storm tracks and points of dissipation used records beginning with the 1956 season. The study of preferred areas for storms crossing the west coast of Mexico used all known data since 1921. The study of gale-force winds in the Gulf of Tehuantepec used ten years of data from the "Rough Weather Log" section of the Mariners Weather Log, beginning in July 1962. Conflicts in dates and positions from multiple data sources were resolved logically in this study. The processed data compiled appear as appendices to this study.

IV. FREQUENCY OF CYCLONES

Establishing the period, general completeness and reliability of records required an extensive search and comparison of data. Ten cyclones in 1954 and six in 1955 were reported by Wilgus (op. cit.). Quinn (1959) stated that the twelve tropical storms of 1957 were more than had been reported since 1945 when complete summaries became available. No year-to-year source of frequencies from 1945 through 1953 were found although the long-term mean from 1945 through 1959 was given by Crooks (1960) as six. From this mean value and the known frequencies from 1954 through 1959 a total of thirty known storms are estimated for the period 1945-1953. More complete records of annual frequency and strength began with the 1956 season, as reported by Quinn (1957) in the first volume of Mariners Weather Log. That year marked the first year of adequate data for most aspects of this study. FWC Alameda records, including the number of warnings and warning days, beginning in 1962, were reported in the Annual Typhoon Report 1965, the first such issue to cover EASTROPAC cyclones.

Table I records the results and reports mean values of annual frequencies for tropical depressions, tropical storms and hurricanes for the seven years of reasonably complete operational satellite coverage. Only tropical storms and hurricanes were used for the frequency study. The validity of some tropical depressions remains questionable and no

records of tropical depressions were kept prior to 1965. Table I indicates an annual frequency of 14.6 for combined tropical storms and hurricanes for the seven-year period 1965-1971, an increase of 5.2 cyclones or 55 percent over the 9.4 cyclones of the seven-year period 1958-1964. Much of this increase must be attributed to increased detection capability through use of operational weather satellites.

Cyclogenesis as used in this study refers to the first day a cyclone was declared to have reached tropical depression or a higher state of development. Only those storms eventually reaching tropical storm or hurricane strength were included.

Appendix D, containing records of 219 tropical storms and hurricanes, was assembled to define the EASTROPAC tropical-cyclone season and study the distribution of cyclogenesis within the season. The seasonal distribution of cyclogenesis is depicted in Figure 3 which shows a sharply defined six-month season extending from 15 May through 15 November. The tri-modal distribution curve is unique among major areas of tropical cyclogenesis. Cyclogenesis in May and November is infrequent and minimum periods of activity occur in early August and late September. Semi-monthly distributions for the period 1921-1971 and 1965-1971 are tabulated in Tables II and III, respectively. Day-by-day frequencies of cyclogenesis occurring within the season are summarized in Table IV.

To compare the frequencies of cyclogenesis between the Atlantic, WESTPAC and EASTROPAC areas, the respective generation areas and seasons should be considered. The EASTROPAC formative area depicted in Figure 2 is less than one fifth the size of the primary WESTPAC area in the Philippine Sea and about the same size as the Gulf of Mexico. The EASTROPAC season closely parallels the Atlantic season in length but produces twice as many tropical storms or hurricanes from only one fourth the area. WESTPAC has seen the formation of tropical cyclones in every month and has many times the area of EASTROPAC. Adjusted for season and area EASTROPAC is the most prolific area in the world for tropical cyclogenesis. This fact justifies further research in this geographic region.

A reasonable question might be raised concerning possible inter-relationships between eastern and western Pacific tropical areas. Simpson and Frank (1970) have viewed the eastern Pacific region as merely an extension of the Atlantic area. Cry and Haggard (1962) pointed out that the frequency of cyclogenesis in the western Caribbean area has a dual mode with the "season" from approximately 15 September to 15 November. Sixty-three percent of all cyclones form during this period. A secondary minor peak in May and June is present, but formation from 1 July to 15 September is unusual. This distribution is inconsistent with the concept of EASTROPAC being essentially an extension of the Atlantic area since the frequency distribution of cyclogenesis in the eastern Pacific

(Figure 3) is inversely related with that in the adjacent western Caribbean area.

To investigate possible relationships between the eastern and western regions of the tropical Pacific Ocean the frequencies of cyclogenesis in both areas were compared. It was first postulated that a linear relationship between the two areas should produce a constant ratio of frequency while a non-linear but positive relation should retain the same sense of proportionality. Also, changes in western Pacific cyclone frequency between successive years should correlate with a consistent sense of change in EASTROPAC cyclone frequency. Table V indicates that five of the six percentage change pairs agree in algebraic sign, but no systematic relationship in the magnitude of changes can be seen between WESTPAC and EASTROPAC. It appears that the variation in ratio is too great to support a linear relationship. The eastern Pacific exhibits considerable independence in frequency of cyclogenesis as compared to activity in the western Pacific although Table V shows that an increase in frequency in one area is generally accompanied by an increase of frequency in the other.

Table VI presents the same comparisons between Atlantic and EASTROPAC areas but shows differing results. The algebraic signs of year to year change are generally opposed between the Atlantic and EASTROPAC. Further, the ratios of EASTROPAC to Atlantic cyclones range from 0.8 to 2.7, and, like WESTPAC vs EASTROPAC, no simple linear relationship in

frequency appears to exist. Comparison of changes from year to year shows a negative correlation in four of five cases with years of high activity in the Atlantic generally corresponding to low-activity years in EASTROPAC.

The foregoing does not preclude the existence of large-scale features or teleconnections between the three main regions of tropical cyclogenesis. The distance between the Atlantic and EASTROPAC formative areas is about 60 degrees longitude (45W to 105W) while this distance measures 90 to 120 degrees (105W to 165E to 135E) between the EASTROPAC and WESTPAC areas. These distances are on the scale of long waves. If it is assumed that there exists an optimum position for tropical cyclogenesis relative to the long-wave pattern in the westerlies then it can be shown that given cyclogenesis in the Atlantic near 45W, conditions in the EASTROPAC formative region will be equally favorable with respect to this scale of motion only when long-wave number six prevails in the area 45W-105W. Long wave number three, of length 120 degrees longitude, would be 180 degrees out of phase while wave numbers five and four represent intermediate conditions. Wave numbers three and four (90 to 120 degrees) would place the EASTROPAC area in phase with some part of the WESTPAC formative region. Wave number five gives an in-phase relationship between EASTROPAC and the South China Sea.

No climatology of long waves in the westerlies at lower latitudes was found in a search of the literature. Wave numbers three and four are common in mid-latitudes and six is

uncommon. The influence of long waves in the westerlies on tropical cyclogenesis might be studied using synoptic long-wave charts (such as FNWC's SL analyses) on days when cyclogenesis is occurring in more than one of the major regions. A persistent deep trough at upper levels of the atmosphere along 125W in 1968 was noted by Gustafson (1969) to result in a favorable upper col area over the usual area of formation in EASTROPAC. The relationship of large-scale features of the upper tropospheric circulation to tropical cyclogenesis in EASTROPAC is believed to be a fruitful area for further research.

V. DURATION OF CYCLONES

The mean durations of EASTROPAC tropical cyclones by month were segregated into pre-satellite and post-satellite years in Table VII to demonstrate the anticipated effect of satellite surveillance. The effect was hardly less than dramatic with nearly two days added to the mean duration of EASTROPAC tropical cyclones following the introduction of operational satellites. This is a 38 percent increase in duration and warnings in the cyclones detected. Combined with the 55 percent increase in the number of cyclones detected, an apparent increase of 114 percent in tropical cyclone activity between the last two seven-year periods can be shown. A further slight increase in cyclogenesis might be anticipated if the sample were again segregated to show the effect of the introduction of night-time satellite coverage in 1970. Rapid development of EASTROPAC cyclones should result in issuing many first warnings during hours of darkness when most ships do not normally send reports. The relationship between time of day and rate of intensification has not been established but may be a matter worthy of investigation when a sufficient data base has been compiled.

The distribution of duration within the season is shown in Table VIII. We observe that early-season and late-season cyclones are not as long lived in the mean as are mid-season cyclones. The more extensive favorable area and straight

tracks in mid-season are probably responsible for most of this difference.

VI. SIZE OF CYCLONES

The mean radius from the eye of a tropical cyclone to the outer closed isobar of the surface analysis has been commonly used as a measure of the size of western Pacific tropical cyclones. This method is subject to large variations in apparent size because of sparse data density and the subjective nature of the surface pressure analysis.

The concept of mean circular cloud diameter was introduced to define a parameter for estimating the maximum tropical cyclone winds from satellite photography. The mean circular cloud diameter of a tropical cyclone is logically related to the cirrus outflow area and spans the cyclone within the outer band of subsidence. This parameter is relatively more accurately determined in EASTROPAC than is the radius to the outer closed isobar of the surface analysis because of a very sparse data presentation for EASTROPAC surface analysis and the several good satellite pictures available daily for the same area. The use of mean circular cloud diameter as a tropical cyclone descriptor is suggested as an improved climatological, research and operational parameter.

The mean circular cloud diameters of 40 recent tropical cyclones of the EASTROPAC were measured from ITOS-1 and ESSA satellite pictures and compared with 24 tropical cyclones of the same period from WESTPAC. The results are summarized in Table IX.

The standard deviation of WESTPAC (sample two) was increased considerably by two very large typhoons: Gloria (1969) 6.5 degrees and Joan (1970) 7.2 degrees. By excluding these two cyclones from WESTPAC sample three, the standard deviation of 1.0 degrees for the whole sample was reduced to 0.6, comparable with the variability found for EASTROPAC.

The difference in mean values of the two samples objectively supports the observation of the National Weather Service forecasters Denney(1971) and Baum (1966, 1967) that eastern Pacific tropical cyclones are indeed smaller than tropical cyclones in other areas. The mean EASTROPAC cyclone covers an area only one half that of the tropical western Pacific cyclone. The sample of EASTROPAC cyclones is normally distributed about the mean diameter of 3.3 degrees in Table IX. Only two of the sample of 40 cyclones are equal in diameter to the mean of western Pacific cyclones. The minimum diameter of EASTROPAC cyclones are subsynoptic in the scale of operational numerical grid lengths.

EASTROPAC cyclones with mean circular cloud diameters of 1.5 degrees or less are interesting since they are only four percent of the size of Typhoon Joan and twenty-one percent of the size of the mean EASTROPAC cyclone. They represent only a small part of the total frequency and would be unimportant if only small diameter could be equated with small intensity. The research vessel Robert Conrad documented Hurricane Eileen on 26 August 1966 as having a five-mile-wide band of 60 to 70 kt winds about an 8-by-12-mile

elliptical eye and reported the heavy rain band to be only 10 miles wide. Maximum seas of 25-30 ft decreased to only a few feet at a distance of 80 n mi from the eye. The radius of 40 kt winds was about 45 n mi.

The San Juan Trader was reported in Mariners Weather Log to have passed near the eye of a hurricane on an eastward course on 9 June 1956 and experienced 85 mph (73 kt) winds at 15.5N 106.0W. One hour later winds were 29 mph (25 kt). The mean storm speed at that latitude is 12 kt and the movement of the ship under those conditions was probably not more than 15 knots. The radius of 25-kt winds for this storm was estimated to be only 30 n mi and yet contained winds of more than hurricane force.

As reported by Benkman (1963) the S.S. Golden State encountered winds of force 8 (37 kt) for about an hour on 21 August 1962 and estimated the width of the disturbance at 20 n mi.

Hurricane Rebecca (5-11 October 1963) had one of the lowest pressures reported for an EASTROPAC cyclone (965 mb) and winds of 90 kt, yet the radius of 35-kt winds was only 40 n mi.

Hurricane Inez in the north Atlantic area is included among the "great hurricanes" by Kraft (1966). As such it had a minimum pressure less than 945 mb and maximum winds of over 120 kt. Yet Inez has been analyzed as an example of a "mini-hurricane" by Hawkins and Rubsam (1967). Inez had a mean circular diameter of 3.5 degrees, very much the same as that of a typical EASTROPAC cyclone, emphasizing

again that great size is not a requirement for great intensity. "Great hurricane" Camille had a diameter of only 4.2 degrees, somewhat greater than most EASTROPAC cyclones, but less than the average found for western Pacific systems.

Another point of interest is the ability of a single diameter to represent a cyclone which exists over a period of days. There appears to be an individual characteristic circular cloud diameter for many cyclones. For example Hurricane Denise, 1971, presented a series of well-defined views on 6-8 July 1971. While traveling from 12N 117W to 14N 134.5W she maintained a constant cloud diameter of 3.3 degrees of latitude even though increasing in intensity from 60 to 80 kt. Hurricane Monica had a constant diameter of 3.3 degrees on 31 August and 1 September 1971 when she was described as the strongest hurricane observed by aircraft reconnaissance in the eastern Pacific. Surface winds of 100 kt were estimated for Monica on 1 September, a 50 percent increase in 24 hr. The cloud diameter of Hurricane Lorraine increased from 3.6 degrees on 22 August to 4.8 degrees on 23 August 1970, about the time Lorraine was downgraded to a tropical storm. The second largest diameter in the eastern Pacific sample was thus associated with decreasing intensity. The circular appearance and distinctive eye of Lorraine were still prominent on the 23rd. An increase of 78 percent in area accompanied a decrease in maximum wind. Denney (op. cit.) describes this in the 1968 season as a filling cyclone accompanied by a significant increase in the radius of

maximum winds. This has been referred to as "blow up" of typhoons in the western Pacific and has been associated with extreme apparent eye diameters of the order of 200 n mi.

It would appear that peripheral structure varies considerably more than does the central core of tropical systems. This is yet another reason to reserve judgment as to the danger posed to shipping by tropical cyclones in the eastern North Pacific. Their smaller size aids greatly in their avoidance as does the infrequency of erratic tracks and recurvature, but the systems often have sustained winds of 100 kt near their compact central cores and are capable of dealing roughly with the unwary mariner who fails to yield the right of way.

VII. SPEED OF CYCLONES

Since 1965, FWC Alameda's post-season analysis of best-track and other data has been available for hurricane strength cyclones in EASTROPAC. In the seven-year period ending in 1971, 37 hurricanes have been documented. This sample was used here to establish climatological tracks and speeds since it represents the best available set of evaluated data.

Best tracks for EASTROPAC cyclones display more short-term variability in speed and track than is common for the western Pacific. This may be explained mostly by the relative infrequency of aircraft fixes in EASTROPAC. The accuracy of satellite fixes according to the Fleet Weather Central, Guam Annual Typhoon Report (1971) is on the order of 30 n mi. The accuracy of locations determined from ship reports alone does not approach even this value. Frequent aircraft reconnaissance fixes with an accuracy of 10 n mi or less in the western North Pacific support relatively smoother variations of course and speed in that region. Therefore, the EASTROPAC track chart (Figure 4) has been based on mean course and speed in five-degree grid squares. Usually the five degree crossing time is an 18- to 36-hr period except for tracks intersecting grid corners. Using increased satellite coverage and accumulating additional years of data, a chart based on 2.5 degree grid squares, such as Hope and Neumann (1971) applied to the Atlantic, would be a welcome refinement to this initial product. At this point, however,

the author believes it to be an unwarranted extension of data accuracy and sample size.

A typical cyclone begins and ends at a slower speed than that observed during the hurricane stage, particularly when detected early in the formative stage. Some cyclones were first detected in the tropical-storm stage somewhat to the west of their probable areas of origin. Initial speeds in these cases were equal to the mean cyclone speed. The distribution of cyclone-track directions shown in Figure 5 implies a high frequency of nearly straight tracks. A family of curves has been drawn to fit the central means of speed in Figure 6. Considering the many factors affecting cyclone speed the data fit the curves rather well. Figure 6 is suggested as a forecast aid for estimating initial cyclone speeds and for use in forecasting speed changes based on the latitude changes of the forecast track. Table X gives the distribution of maximum speeds observed and is a useful guide for this forecast.

Cyclone speed is slightly dependent on direction of cyclone motion in that speeds for courses clockwise from 310 degrees decrease in a regular fashion as seen in Figure 7. Speeds up to one knot higher than the sample average of 10.3 kt are found for courses from 275 through 315 degrees.

FWC, Alameda watch-officer narrative reports, giving the logic of positioning and forecasting Patricia (1970), reveal that extrapolation was the only reliable tool available in nearly half the warnings and was an important tool in all the

remaining warnings. Thus, the method of extrapolation becomes an important consideration in attempting to minimize forecasting errors.

Accuracy of center-fix locations is the basis of accuracy for determination of course and speed and therefore the extrapolation forecast. The FWC, Guam Annual Typhoon Report (1971) discussed the accuracy of locating tropical-cyclone centers by various methods, giving median errors of 7.5 n mi for aircraft fixes and 19.5 n mi for satellite fixes on tropical storms with winds of at least 60 kt and having a visible eye. Less intense storms and tropical depressions were found to have median errors of 9.5 n mi for aircraft fixes and 35.5 n mi for satellite fixes; however, the 1971 experience in the western Pacific found visible eyes present only 25 percent of the time so the larger error applies more frequently.

Applied to the EASTROPAC area and the problem of forecasting by extrapolation it is found that fairly large errors in speed determination are likely with only six hours between fixes. A cyclone moving at the mean EASTROPAC speed of 10.3 kt covers 61.8 n mi in six hours. Were two aircraft fixes of nominal 7.5 n mi accuracy available over a six-hour interval, the derived apparent speed may vary from $\frac{61.8 - 15.0}{6}$ or 7.8 knots to $\frac{61.8 + 15.0}{6}$ or 12.8 kt. This speed determination, based on the most favorable aircraft accuracy, contributes a maximum of 60 n mi per day to forecast error. Table XI shows the ranges of apparent speeds for various fix methods over

various time intervals, assuming a true uniform speed of 10.3 kt. The numbers representing maximum contributions to 24-hour forecast error provide a means of evaluating the combined effects of fix method and fix interval. If a storm moves with uniform speed, the accuracy of determining that speed increases with increasing time intervals between fixes. Fix methods of greater initial accuracy converge to the "correct" solution in a shorter time interval. Thus, aircraft reconnaissance fixes six hr apart theoretically produce a speed estimate of nearly the same accuracy as that determined from satellite fixes sixteen hr apart. The probability of a cyclone maintaining a constant speed, as assumed in this case, for the period between fixes plus a 24-hr forecast period is considerably better for the 30-hr period involved with the aircraft data case than for the 40-hr period of the satellite case. Mean-speed estimates between two fixes are more accurately determined over longer averaging periods, but are less useful for extrapolation, since the assumption of constant speed becomes less valid with increasing time.

In actual operation, aircraft reconnaissance has been limited to one flight per day. Time on station and the maximum time between aircraft fixes over the cyclone center is limited by aircraft endurance to five or six hr. Satellite observations, on the other hand, are usually available at intervals of about 12 hr. Geostationary satellites can provide a fix approximately every 30 minutes during daylight hours. Mean satellite fix accuracy in EASTROPAC is probably

better than that reported for WESTPAC because of the presence of identifiable coastline features in many passes containing cyclones and because of the generally smaller diameter of EASTROPAC cyclones.

The most common determination of speed will be made from two satellite positions twelve hr apart with no visible cyclone eye. The maximum speed-determination error in this case is 5.9 knots. This is nearly equal to two standard deviations of the mean climatological speed from Figure 8. Climatology speed is less prone to error than short-term speed determination and should be used for forecasting cyclone speeds until a more accurate fix can be obtained and/or a longer period between fixes can be used to increase the accuracy of speed determination. A reversion toward climatology is in order for most speed estimates because of the nature of speed distribution shown in Figure 8. The dependency of EASTROPAC cyclone speed on latitude has been demonstrated in Figure 6. It should be possible to improve on climatological and extrapolative speeds by applying the mean climatological acceleration factors implied in Figures 6 and 7.

Two factors are thus working to move the cyclone at a climatological speed rather than the currently determined short-term history speed. The possibility of error in speed determination has been explored as one argument. The sharply-peaked distribution of observed speeds and the actual daily variation of cyclone speed is another powerful argument to apply to speeds far above or below the median speed.

Consideration should always be given to adjusting the extrapolation speed toward the median climatological speed when forecasting.

VIII. CYCLONE TRACKS

Cyclone-track direction should be handled much the same as speed since cyclones in EASTROPAC are reasonably uniform in direction as shown in Figure 5. The change of direction with latitude,noted in Figure 9, should be used to modify simple extrapolation. Figure 4 shows the trajectories of 37 hurricanes for the period 1965-1971. The trajectories are taken to be representative of all tropical cyclones. The extrapolative track drawn through the center of the last two fixes may be unrepresentative of the true track. The FWC Guam Annual Typhoon Report (1969) credits a majority of the 24-hr forecast error to directional error as opposed to speed error. To minimize directional error in a region of small variations in direction, a longer-term history track covering 24 to 36 hr should be fitted by eye using Figure 4 as a guide. The apparent short-term motion should be modified to approach the forecast track extrapolated with the aid of Figure 4.

Excluding those cyclones moving north of 330 degrees, the modal and mean directions fall near 290 degrees with 80 percent of the tracks within 20 degrees of that value. The peakedness of the distribution curves, Figures 5 and 8, are further indications of relatively consistent behavior of EASTROPAC cyclones as contrasted with Atlantic and WESTPAC tropical cyclones. This consistency can be used to advantage by the marine forecaster. Even though the EASTROPAC conventional weather data network is very sparse and aircraft

reconnaissance is limited, the quality and accuracy of warnings for this region need not be less than that achieved in the Atlantic and western North Pacific regions.

Recurving cyclone tracks are those westward tracks that turn anticyclonically until there is a component of motion toward the east. These are the most difficult tracks to forecast accurately in the Atlantic and western Pacific and present serious problems for units operating in these areas. The frequency and nature of recurving cyclones in EASTROPAC is therefore a matter of interest in this study.

Appendix B is a sixteen-year chronology of all known EASTROPAC recurving cyclones. Over this period it is noted that only 15 percent of the total cyclones recurved, a frequency of 1.8 recurving tracks per year. The record of the yearly frequency of recurving cyclones is found in Table XIII.

Burrows (72) studied recurving cyclones of the western Pacific and found a 40 percent seasonal recurvature value. His values for recurvature frequency within the season are shown in Table XIV for comparison purposes. We note from Table XIV that EASTROPAC recurvature is rare in May and June and unknown in July and August. In September, however, the likelihood increases to approach that of the western Pacific. In October EASTROPAC recurving tracks become as frequent as westward tracks.

The main danger in recurving cyclones of the Atlantic and Western Pacific lies in their sometimes radical acceleration as they enter the zone of strong westerly winds north of the

subtropical ridge. From behavior of recurving cyclones in the Atlantic and western Pacific it might be anticipated that EASTROPAC cyclones would decelerate approaching the subtropical ridge, slow in movement through the ridge and accelerate in easterly motion north of the ridge, with the mean speed after recurvature greater than the mean speed before recurvature. Table XV shows the behavior of eastern North Pacific recurving cyclones compared to the "classic" recurvature case. We can identify only four "classic" recurvature cases among the fifteen cases with enough data to make comparisons on all characteristics. Individually we note that two-thirds of the cyclones decelerate as they begin recurvature, but only about one-half accelerate after recurvature or reach a speed higher than the speed before recurvature. The average maximum speed after recurvature is only increased by 1.2 kt, indicating that large accelerations are not usual. The highest speed observed after acceleration was 20.0 kt and the second highest 16.5 kt of 26 cases having information after recurvature.

Recurving cyclones in the eastern Pacific do not generally follow the classic behavior of recurving cyclones in the Atlantic or western Pacific. They are characterized by slower mean speeds (7 to 8 kt) before recurvature and little if any acceleration after recurvature. Their track following recurvature can be empirically predicted as a function of the mean track before recurvature by using Figure 10 or Table XVI. The normal latitudes and areas of recurvature are displayed in Figures 11 and 12.

The behavior of EASTROPAC recurving cyclones resembles that of cyclones in the western Pacific recurving near the mean recurvature latitude of EASTROPAC cyclones. WESTPAC cyclones recurving below 20N showed accelerations after recurvature of less than one knot per six hours in all months (Burrows, op. cit.). Speed following recurvature is largely independent of direction in EASTROPAC, where higher speeds following recurvature are associated with higher speeds before recurvature, (Table XVII). The zone of westerlies north of the subtropical ridge in EASTROPAC is apparently not strong enough to produce large accelerations.

Various methods of prediction of the post-recurvature track were attempted:

1. Latitude vs sharpness of recurvature
2. Latitude vs post-recurvature track
3. Longitude vs sharpness of recurvature
4. Longitude vs post-recurvature track
5. Month vs sharpness of recurvature
6. Month vs post-recurvature track

Only method 3 revealed a usable relationship. The results of method 3 are presented in Figure 13. Armed with Figure 13 as a forecasting tool it is necessary only to find a means of identifying those cyclones which will recurve and their latitude of recurvature to produce a climatologically "perfect" track forecast. The climatological mean latitude for recurvature, modified by satellite cloud pictures, should locate the synoptic-scale ridge latitude with fair accuracy.

By following the extrapolated track and the climatology trajectory (Figure 4) to the points where they intersect the latitude of the ridge (determined prior to the time it was distorted by the tropical cyclone) it is possible to localize the area and time of possible recurvature. The wind direction and time cross section at Ocean Station November and the 700-mb and 500-mb forecast charts for the possible recurvature time might then be used to establish the presence and depth of an upper-level trough sufficient to cause recurvature. The speed following recurvature was shown not to be a particular problem. Deceleration in the ridge of 30 percent followed by 30 percent acceleration to regain the mean pre-recurvature speed in 12 hours would be a first approximation. Intensity following recurvature should be viewed as a function of sea-surface temperature. A more complete study of the relation between winds at Ocean Station November and the known cases of recurvature and non-recurvature is needed to establish objective rules for this occurrence.

Of all tropical cyclones forming in the eastern Pacific, 70 percent die at sea and 30 percent strike land. Unlike the western Pacific, the recurving cyclones of the eastern Pacific are the ones which most frequently strike land while the straight-running, westerly-moving cyclones find unfavorable conditions, weaken and die over water.

The distribution of areas where cyclones cross the coast is not random. Of those cyclones which cross the coast, 29

percent cross between Acapulco and Manzanillo over a coastline distance of about 280 miles; 18 percent cross near Mazatlan over a 90-mile stretch of coast; 14 percent strike over 60 miles of coast on the south tip of Baja California; 13 percent strike the west coast of Baja south of 27.5N over a 300-mile distance and 11 percent cross north of 30N. This last value is undoubtedly higher than it should be since five of the seven cyclones are from pre-satellite records and reflect the increasing concern felt when a tropical cyclone approaches the United States. Within the last seven "satellite" years only 2 of 27 or 7 percent of the cyclones crossed this area of the coast. The remaining cyclones (15 percent) are divided between areas north of Mazatlan on the main coast (3), the Gulf of Tehuantepec (4) and on shore near 20N (2). Figure 14 has been constructed to show the areas crossed by 63 tropical cyclones from 1921 through 1971. Table XVIII shows the mean position of recurvature by month and season with standard deviations of latitude and longitude.

A unique feature of some tropical-cyclone tracks in EASTROPAC is their tendency to turn toward the southwest as they approach a central position of 19N 118W. This behavior is inevitably a precursor of rapid weakening with dissipation generally completed five to seven degrees longitude to the west-southwest of the northernmost point of the track within 24 to 36 hours. Seventeen such "hump" tracks have been identified in the period 1956-1971 and are summarized in Appendix H. The mean course to the west-south-west was 256

degrees with a standard deviation of only 3.5 degrees. The mean distance to the point of dissipation was 450 n mi although 12 of the 17 cyclones dissipated before covering 400 n mi.

Eight of the seventeen tracks turned within one hundred miles of 19N 118W. Six cyclones executed the same tactic further to the west and only one track of this type was found to the east of the main group. The hump track has occurred only in the months of July, August and September. It has been described in the present study without attempting to explain it or relate it to synoptic causative features. It is noted that the location of most frequent occurrence lies immediately beneath the eastern edge of the semi-permanent high. The influence of the high probably accounts for the change in cyclone course. This is a tentative explanation awaiting further investigation.

IX. FORMATION, INTENSIFICATION AND DISSIPATION OF EASTROPAC CYCLONES

A. FORMATION

Gray (1970) used records extending back to 1948 to estimate a yearly frequency of 10 EASTROPAC cyclones of tropical storm or hurricane intensity. This study now estimates 15 such cyclones per year. Updating Gray's figures for global cyclogenesis in the tropics with this information produces a worldwide total of 67 tropical storms and hurricanes per year with 22 percent occurring in the limited area of EASTROPAC.

LaSeur (1966) states that "hurricanes are unique and rare combinations of several scales of motion, each of which plays a vital role and the sum of which combine to form the hurricane". Many previous studies of tropical cyclogenesis concentrated on synoptic-scale motion. The climatological approach of this study focuses on longer time scales and an expanded space scale. Formation of tropical cyclones with respect to large scale atmospheric features was discussed in Section IV of this study where the assumption was made that there exists an optimum relationship between the long-wave pattern of the upper troposphere and cyclogenesis in the EASTROPAC region.

Intermediate-scale analysis, as illustrated by space-mean charts, has been applied to develop the concept of "steering" tropical cyclones by the mean atmospheric flow at one or several levels. The tendency of tropical cyclones to follow

the periphery of the intermediate-scale anticyclones has provided a useful forecasting tool where reasonably accurate analysis can be made.

Radar studies and aircraft reconnaissance have clearly shown the dependence of tropical storms on convective scale substructure in the eye-wall cloud and in rain bands. Gray (op. cit.) has postulated that large-scale circulation creates areas favorable to cumulus-scale convection by producing minimum vertical shear areas over water where the sea-surface temperature is greater than the air and greater than 78F. In these relatively unstable areas turbulent-scale motion, with dimensions in tens of meters and time scale in seconds, is effective in the exchange of sensible and latent heat in the air-sea boundary layer.

The inter-dependence of these scales was illustrated by Bjerknes (1969) who described a two-year cycle of the Hadley Cell and surface water temperatures along the equator. The heat exchange available beneath the favorable atmospheric shear zone is a direct function of ocean-surface temperature. The frequencies of EASTROPAC cyclogenesis were computed from Table I for odd and even years in the period 1965-1971; however, no significant difference was found related to a two-year cycle. Either surface water temperature in the formative area is not subject to the same two-year variation cycle found by Bjerknes for central Pacific equatorial waters or other factors predominate in determining the season.

According to Carlson (1971) no tropical storms have been known to form over water cooler than 78 to 80F. Perlroth (1967) found a high correlation between narrow zones of relatively cold and warm water crossed by a traveling tropical cyclone and decreases and increases, respectively, in cyclone intensity. From this observed rapid response by cyclones to warmer or colder water underfoot it might be postulated that mean seasonal strength as well as frequency of formation in EASTROPAC is, in large part, influenced by sea-surface temperature anomalies beneath the region of favorable atmospheric vertical shear.

The climatology of sea-surface temperature for August (Figure 15) suggests that cold water is a limiting factor to both the south and the north of the formative area. Favorable air-sea temperature differences exist only in the relatively narrow zone between the 80F isotherms. The limiting effect of this isotherm is dramatically shown by the fact that it separates the area of origin on Figure 2 from the area of dissipation on a climatological scale. No cyclone was observed to form in the area of climatological sea-surface temperatures less than 80F and only a few cyclones dissipated in the area of temperatures greater than 80F.

The entire area of favorable water temperatures does not, however, serve as a generation area for tropical cyclones. Only 25 to 30 percent of the warm water zone is effective in initiating cyclogenesis. The northwestern "pan-handle" of the region of cyclogenesis (Figure 2) experiences water

temperatures less than 80F in May and June and, as expected, no cyclones form in that region during that time period. A lower density of formation east of 93W in 80F surface water might be explained by cooler subsurface temperatures. In this region, water 5 to 15F cooler will be brought to the surface by vertical turbulent mixing to 100-ft depths. An initial disturbance can begin with a favorable air-sea energy exchange, but the rising winds produce turbulent mixing, bringing colder water to the surface to reverse or limit the tendency to develop.

Gray (op. cit.) presents a shear climatology for the layer 950 mb to 200-mb to demonstrate that cyclogenesis takes place only where water temperatures are greater than 80F and vertical shear values are less than 10 knots. The coincidence of these two conditions establishes convective instability as a necessary but not sufficient condition for cyclogenesis. The final factor lies in synoptic-scale instability manifested by a low tropospheric positive vorticity center coincident with the area of formation. This is often referred to as a trigger mechanism for initiating CISK.

Much research has been directed toward finding trigger mechanisms (pre-existing disturbances). Mechanisms postulated include ITCZ disturbances, non-ITCZ enhanced convective areas, tropical waves, upper cold lows and lower atmospheric lows on a weak baroclinic zone. Frank (1970) stated that "the main inhibiting factor for tropical cyclogenesis is

related more to prevailing circulation features than to a lack of potential hurricane disturbances." He reported 43 disturbances moving into EASTROPAC from the Atlantic in 1969 initiating most of the EASTROPAC storms. His breakdown of 1968 and 1969 effective mechanisms was 2 Atlantic easterly waves, 3 Caribbean easterly waves, 6 ITCZ disturbances in the Caribbean, 7 ITCZ disturbances in EASTROPAC and 11 African waves.

Namias (1969) and Perlroth (1969) have attempted to relate sea-surface temperatures in the path of African disturbances to the potential for growth into Atlantic tropical storms. Carlson (op. cit.) has related mean seasonal activity of tropical cyclones to ocean temperature anomalies in the area from 10N to 20N and 30W to 40W (a normal Atlantic formative area). He found that 1966 and 1969 were marked by above average sea-surface temperatures and active tropical cyclogenesis, while 1968 (an inactive year) had temperatures 2 to 3F lower in the month of August.

The eastern tropical North Pacific displays considerable interannual variation in the number and strength of tropical cyclones. The 1964 season was below average in both respects with only six storms forming and only one of these reaching hurricane intensity. The 1971 season, by contrast, witnessed the formation of 17 storms of which 12 reached hurricane intensity. We might reasonably infer significant differences between the two seasons in convective, synoptic- and planetary-scale parameters important in the formation of tropical

cyclones. The relative frequency of "trigger mechanisms" such as "African" or "easterly" waves might be an initial basis for an attempt to explain seasonal variability. The trigger mechanism logically represents an integrated lower atmospheric contribution which requires favorable heat exchange from the surface and small vertical shear in order to develop. Simpson (1969) commented on the unusually large number of waves and disturbances crossing the Atlantic during the minimal 1968 hurricane year in the Atlantic. Only seven of 110 tropical disturbances reached tropical storm strength and only four of these became Atlantic hurricanes. Thus, the 1968 Atlantic season has a positive correlation with the sea-surface temperature anomaly, but a negative correlation with an anomalously high frequency of "trigger mechanisms". The EASTROPAC in 1968 was subjected to a similar high frequency of "trigger mechanisms" but with dramatically differing results. An active year was recorded here where 19 tropical cyclones formed. Six of them were designated as hurricane strength. It is concluded that the relative frequency of trigger mechanisms is not as significant as the underlying sea-surface temperature in producing tropical cyclones.

The mean of 30-day-average sea-surface temperatures at the points of formation of 18 cyclones in 1970 was 84.3F. A similar mean at the points of dissipation was 78.2F. Using climatological vertical gradients at the individual points of dissipation the mean temperature at 100 feet was inferred

to be 75.5F. The results agree with the climatological data and are a step nearer to the synoptic conditions existing at the time of cyclogenesis. The tendency for a cyclone to mix the subsurface water and cool the surface (Brand 1970) will moderate monthly-mean surface temperature values along the track of tropical cyclones.

The surface temperature deviations from long term means noted for individual cyclogenesis range from -2 to +2 degrees with eight positive anomalies, three negative anomalies and three zero anomalies at the point of formation. Applying cyclogenesis occurrence on the same scale as temperature analysis, monthly correlations in 1970 show positive surface-temperature anomalies in four months for the generation area. Each of these months have above-average frequency of cyclogenesis if tropical storm Selma, which was discovered west of the usual formative area on 1 November, is properly credited to October cyclogenesis. September had a negative temperature anomaly and less than normal cyclogenesis. The fact that no cyclogenesis was detected after 1 November was normal for a month with an expected frequency of .14. Table XIX shows that the monthly frequency of cyclogenesis relates well to monthly temperature anomalies for the 1970 season, the first season for which anomaly charts were routinely available from the United States Fish and Wildlife Service.

There seems to be general agreement between the seasonal total of weighted central Pacific sea-level pressure anomalies and the observed seasonal frequency of cyclogenesis

(Figure 16). Negative pressure anomalies are associated with positive anomalies in cyclogenesis. The maximum seasonal positive pressure anomaly occurred in 1964, previously identified as an abnormally low year for cyclogenesis. The large negative anomalies of 1967 and 1968 were correlated with high frequencies of cyclogenesis; however, the equally large negative anomaly of 1969 was accompanied by a substantial decrease in frequency of cyclogenesis over the previous two years.

Allison (op. cit.) reported a +.80 correlation between the 700-mb height anomaly and the sea-level pressure anomaly. The 700-mb height anomaly was therefore included in Figure 16. The general agreement between the weighted 700-mb anomalies and seasonal frequency of cyclogenesis is better than the sea-level pressure/seasonal cyclogenesis frequency case. In particular the 700-mb anomaly would explain a decrease in frequency between 1968 and 1969. There is not much doubt that a physical relationship exists between these parameters and EASTROPAC cyclogenesis.

Allison also studied the correlation of cloudiness in various latitude-band average areas. Figure 17 is an interestingly high correlation for the EASTROPAC region between opposite sides of the equator.

The relationship between cyclogenesis from the present study and monthly cloudiness from the Allison study is not a simple one. The presence of a tropical cyclone organizes cloud masses, but does not necessarily increase the integrated

cloud amount. The area of divergence surrounding the cyclone is relatively cloud-free and may cover an area larger than the circular cloud mass of the storm. A second consideration must be made for the type of cloudiness present. The broad mass of stratocumulus clouds found under the southeastern quadrant of the Pacific high pressure cell increases with the amount of cold water while towering cumulus of the Intertropical Convergence Zone increase with the amount of warm water. When the orientation of sea-surface temperature isotherms have a north-south component an average of cloudiness taken along latitude bands (as in the region of EASTROPAC cyclones) contains mixed cloudiness types and the effects of sea-surface temperature anomalies are masked. A general random correlation between band-average cloudiness and cyclogenesis results.

A "shadow zone" within 100 n mi of land seems to exist. Only two tropical cyclones have been plotted as originating closer than this to land. This "shadow effect" is probably related to the scale of these storms and the requirement for an over-water trajectory of air parcels converging toward the surface center of a developing system. A similar shadow exists within 120 n mi of the northern limit of the 80F isotherm.

B. INTENSITY

Twenty-nine of 59 or 49 percent of tropical storms identified in EASTROPAC were evaluated to have reached

hurricane strength. This compares to a report by Cry (1966) that over a 30-year period 32 percent of tropical cyclones in the Gulf of Mexico became hurricanes. The 26-year record for WESTPAC, calculated from tables in the FWC, Guam Annual Typhoon Report (1970) produced a 70 percent figure while the WESTPAC record for the same years as the EASTROPAC study was 65 percent. We conclude that intensification to hurricane strength in EASTROPAC appears to be significantly less frequent than in WESTPAC but more frequent than in the Gulf of Mexico.

A study of the climatology of "super" typhoons (evaluated maximum winds in excess of 130 knots) in WESTPAC was reported in the FWC, Guam Annual Typhoon Report (1970). For the period 1966-1970 there were 16 "super" typhoons representing 19 percent of the designated typhoon strength storms and 12 percent of the total number of tropical systems stronger than tropical depressions. Within the season, occurrence of super typhoons is twice as likely after September first as it is during the early season.

Super hurricanes are notably infrequent in EASTROPAC. Classification of cyclone intensity from sparse ship reports and infrequent aircraft reconnaissance leaves room for questioning the classification of a few individual storms, but the convincing evidence from the statistical distribution of reported pressures and winds is that EASTROPAC cyclones have been quite accurately assessed as weaker than their western Pacific cousins. Only the Manzanillo Hurricane of 22-27

October 1959 comes close to "super" status. Sustained winds of 127 kt occurred during this disastrous storm and winds up to 150 kt were estimated (Fuller 1960). Only a few ship reports per year of full hurricane force winds have been recorded. The most frequent strength of winds reported in passages through the eye has been in the 70 to 90 kt class. A nominal rate of 30 kt of intensification per day was found for western Pacific tropical cyclones by Brand (1971). Applying this value arbitrarily to the eastern Pacific area it is found that moving systems are duration-limited in development since they usually do not remain within the favorable generating area longer than about 3 days. It is postulated that slower-speed storms within the favorable area reach greater intensities (and lower pressures) or that variations in the extent of the favorable generating area are reflected in the maximum development of cyclones forming. This investigation is left for future study.

LaSeur's (op. cit.) model of hurricane tangential winds based on r, the radius of maximum wind coinciding with the center of the "eye-wall" cloud, implies a direct relationship between eye diameter and the various "percentage-wind" radii. LaSeur chooses the inner edge of the cloud-free annular ring surrounding a hurricane as the limit of hurricane circulation. Using this model it was postulated that smaller eye diameters exist for eastern Pacific tropical cyclones than for the larger cyclones of the western Pacific area. A sample of well defined storm-average eye diameters from 40 eastern

Pacific tropical storms and hurricanes, having a mean storm diameter of 3.3 degrees, had a mean eye diameter of 20 n mi, while well defined eyes from 24 western Pacific typhoons with a mean storm diameter of 4.7 degrees had a mean eye diameter of 21 n mi. Clearly the LaSeur model is not applicable with respect to the horizontal wind profile for EASTROPAC cyclones.

A logical reason for the relative weakness and limited development of EASTROPAC cyclones might be found in the mean hurricane heat potential charts of Heffernam (1972) contained in Appendix G. The EASTROPAC area of cyclone formation has a heat storage potential above 26C of from 4000 to 10,000 calories per cm^2 while the western Pacific formative areas range from 24,000 to 32,000 calories per cm^2. Although there is obviously enough energy to form tropical cyclones in the EASTROPAC, the mean potential for development is much more limited than it is in the western Pacific.

C. DISSIPATION

Dissipation in this study was taken to be the point of dissipation given in <u>Mariners Weather Log</u>. From inspection of points of dissipation, a line (based on two standard deviations) limiting the northern boundary of dissipation extends from the west coast of Baja California at 27N to 22N 140W. This line nearly parallels climatological sea-surface temperature isotherms in July to October and crosses at 30 degrees or less in May and June. The climatological sea-surface temperature beneath this limiting line increases

from 70F in July to 71.5F in October. The centers of tropical cyclones rarely penetrate beyond the position of the 71F sea-surface isotherm. As a storm center reaches this position the leading edge of the storm is influenced by water temperatures in the 60's. The strongest gradient of sea-surface temperature normal to the limiting line occurs between 70 and 80F from the coast of Baja California to 132W. It varies from 4.2F per 100 n mi near the coast to 2.4F per 100 n mi at 132W. The mean gradient is 2.5F per 100 n mi north of the 80F isotherm in the usual area of cyclone dissipation.

To test this idea on an individual cyclone basis sea-surface temperatures and temperatures 100 ft below the surface were taken from FNWC, Monterey <u>Atlas of Monthly Mean Sea Surface and Subsurface Temperature</u> (1971) for each of 120 known points of dissipation over EASTROPAC waters. The distribution of dissipation frequency against temperature is shown for both surface and 100-ft levels in Figure 18. The mean surface temperature at the point of dissipation is a relatively high 77F and some storms dissipated with climatological surface temperatures in excess of 80F. The mean temperature at 100 ft is only slightly lower but the distribution is more definitive. Only two storms dissipated where 100-ft water temperatures were greater than 79 degrees. The steep slope and sharp peak of frequency at 78 degrees suggests a critical temperature, below which dissipation occurs. Initial storm strength, speed and the angle of crossing of

the isotherms are factors involved in determining the ocean isotherms reached before dissipation occurs if in fact ocean temperatures determine this process. A case can be made for effective ocean mixing to at least the 100-ft level by the sharpness of the upper boundary of 100-ft temperature distribution. In general, crossing angles are small on westerly tracks and no larger at 132W than at 122W. There is no apparent reason, based on climatic ocean temperatures, for the observed clustering of points of dissipation between 131W and 134W. Plotting 100-ft dissipation temperatures against longitude and averaging by longitude band produces Figure 19 which should provide a better estimate of the isotherm over which dissipation will occur. While this study is based on climatological temperatures it is intended for use with synoptic temperature charts so that temperature anomalies may be interpreted to affect the strength of tropical cyclones.

There is a certain amount of disagreement on the cause of dissipation of EASTROPAC cyclones. Apart from ocean temperatures Gray (op. cit.) credited unfavorable westerly shear with causing dissipation. Investigating this premise through Sadler's (1972) climatology of upper-tropospheric winds, the 250-mb mean wind along the line limiting the northern boundary of dissipation varied from 20 to 30 kt at the western end and from 5 to 30 kt on the eastern end. During July and August it did not seem likely that shear would be a significant factor at the eastern end of the area

since mean westerly winds were only 5 to 10 kt. A climatological storm track of 290 degrees crosses westerly isotachs at an angle of about 45 degrees entering unfavorable shear three degrees south of the observed limit line of northerly penetration. This makes a fair case for the contribution of shear to dissipation.

The same procedure initially applied to ocean temperatures was used to test shear contribution to individual cases. The 250-mb wind was extracted from Sadler (1972) and the gradient level wind was extracted from Atkinson (1970). The shear between the gradient level and 250 mb was taken to be unfavorable for continued existence of a tropical cyclone if it was greater than 15 kt. The value was arbitrary, but based on Gray's (op. cit.) value of 10 kt maximum shear between 900 and 200 mb for formation areas. Unfavorable shear was associated with 64 of 120 cases (53 percent). This contrasts with the finding of Wachtmann (1968) where a minimum in vertical shear was found over a sample of nine WESTPAC and two Atlantic cyclones dissipating in warm water south of 20N.

Based on Carlson (op. cit.) temperature of the sea surface (and 100-ft level) less than 78F were taken to be unfavorable. Temperatures were unfavorable in 96 of 120 cases. Separately, unfavorable shear occurred four times, all in October, without being accompanied by unfavorable temperatures. Unfavorable temperatures occurred 20 times based on surface temperatures only and 36 times at 100 ft without being accompanied by unfavorable shear. Shear and temperature are

jointly unfavorable in 60 cases and 20 cases are, on the basis of climatology, favorable for the continued existence of the cyclone. These last 20 cases may represent anomalous conditions or inaccurate locations of dissipation and should be individually investigated for cause. These dissipating storms have latitude, shear and sea-surface temperature characteristics in common with the sample studied by Wachtmann (op. cit.). He attributed their dissipation partly to angular momentum transports. Wachtmann treated the EASTROPAC area as an example in his study and cited the decrease in tangential wind between 5 and 10 degrees latitude distance from the center as a cause of dissipation. In view of the mean EASTROPAC cyclone radius of 1.65 degrees it does not seem logical to extend the radial distance for analysis of angular momentum beyond 5 degrees from the cyclone center, especially when a mountainous land mass lies within the region. His data show only minor contributions to momentum transport within five degrees of the center.

Denney (1972) claims that low-level injection of cold air occurs while the center is some distance from the cold water source of that air and is one of the primary causes of dissipation. Such an effect would generally be restricted to the radial distance of the cyclone circulation. The mean northward gradient of temperature in the zone of dissipation is 2.5F per 100 n mi. Under this condition the center of an average size cyclone crossing the 80F isotherm on a northwesterly track has peripheral circulation over 77.5F water.

Dissipation has already begun at this temperature. By the time the center reaches 77F the northern semicircle is over water of 74.5F and dissipation becomes a reasonable expectation. When northerly gradient flow exists in the lower atmosphere this effect can extend for a further 50 to 100 n mi southward. This response of the atmosphere to a warmer sea is quite rapid and it would not be expected to find this effect on centers more than 200 miles south of cold water.

Further investigation with later seasons or using anomaly charts derived from earlier sea-surface temperature charts will be needed to support the conclusions based on the 1970 season. These conclusions briefly summarized are:

(1) The mean sea-surface temperature at the centers of formation of EASTROPAC tropical cyclones is 84.3F. Cyclogenesis will seldom occur in water colder than 83F.

(2) The mean sea-surface temperature at the centers of EASTROPAC cyclones at the points of dissipation is 78.2F. Dissipation may occur with sea-surface temperatures of 80F to 82F on the west coast of Baja California because of much colder water lying near the surface.

(3) Greater than/less than average monthly mean surface temperatures are associated with greater than/less than average frequency of cyclogenesis.

The process of dissipation proceeds at various rates. Recognizing the evidence of dissipation as an ongoing process

is largely a matter of satellite picture interpretation. The following evidences of dissipation are summarized from various annual reports and this study.

(1) Invasion of clouds into the previously clear annular ring of subsidence north of the system is an indication of decreasing subsidence.

(2) The loss of circular appearance and/or less of brightness as the cirrus canopy breaks up and reveals warmer middle and low clouds with vortical structure is the most common evidence.

(3) Cyclonic deformation of the edge of a stratocumulus cloud bank north of the storm indicates incorporation of cooler air from below the inversion level north of the cyclone into the peripheral cyclone circulation.

(4) When the clouds associated with a tropical cyclone are approaching a large rectangular quasistationary cloud mass to the west northwest, the cyclone is entering a zone of upper-level shear in southwesterly winds. Rapid reduction to a tropical depression stage will occur when the two clouds merge. The depression may persist for 24 hr.

(5) Anticyclonic curvature of the storm track, especially while located near 19N 118W is another sign of ongoing dissipation. Typical behavior following this observation is decelerating movement to the

west southwest with dissipation occurring within the next 24 hr.

(6) Deceleration on a northeasterly track following recurvature is an indication of dissipation in 24 to 48 hr.

(7) The mean sea-surface temperature at the points of dissipation of EASTROPAC cyclones is 77F. Gradual dissipation should be anticipated as the cyclone center passes over water cooler than 79F with complete dissipation occurring before the 71F isotherm is reached.

(8) All tropical storms and hurricanes crossing the Gulf of California and also those approaching the southern coast of Baja California will lose intensity due to upwelling of cold subsurface water.

Perlroth (1969) found indications that hurricane development was more likely over nearly isothermal water of high temperature than over regions with a shallow layer of warm water overlying colder water. Leipper and Volgenau (1972) pointed out the logical relationship of this observation to the "heat potential" defined as the heat which could be extracted from the water column to reduce it to an isothermal temperature of 26C. Their estimate of heat loss by the ocean to a passing hurricane is about 4000 calories per day of exposure. The diameter of an EASTROPAC hurricane is about 200 n mi and its mean speed is 10.3 kt. A passing EASTROPAC hurricane will be over a given elemental water

column for a maximum of 19.4 hr. A random encounter of a storm with the elemental column would be along a 172 n mi chord midway between the center and the periphery. The normal EASTROPAC cyclone thus would extract a mean of 2800 cal/cm^2 from the ocean over a 16.7 hr period. The rate of heat exchange is dependent on the surface temperature and decreases as the surface cools. Considerably more than 2800 cal. of heat storage value would be required before that amount of energy could be withdrawn. Should the storm move over regions where the available energy is less than sufficient to exchange 2800 cal. in 16.7 hr, the storm will weaken. Further intensification would not be expected after the cyclone moves to an area with less than about 4000 cal. per cm^2 of heat storage. It is suggested that the 4000 cal/cm^2 isoline determined from the most recent ocean analysis prior to the time of forecast should be used to mark the geographic line of maximum intensity of a moving EASTROPAC cyclone. Climatology of this line may be found in Appendix G.

X. OCEAN WAVES PRODUCED BY TROPICAL CYCLONES

Ocean waves produced by tropical cyclones are among the most serious hazards to shipping and deserve special consideration by the marine forecaster in connection with the wind fields present. According to the statistical wave energy theory of Pierson, Neumann and James (1955) an exceptionally high wave will occur in any wave system after a long enough time. If the forecast wave height is generally taken to be the significant wave height or the average height of the highest one third, the highest wave of 20 will be 122 percent of the forecasted wave height. In a study by Pore (1957) the average observed wave period was six to nine seconds for all quadrants of five Atlantic hurricanes. One Gulf of Mexico hurricane had a mean wave period of eleven seconds. Depending on relative motion to that of the waves a ship would experience about 300 to 600 waves during any one-hour period. Thus the heights of the highest of 500 and highest of 1000 waves need to be considered in the usual time scale of exposure for ships in the wave train of a tropical cyclone. Most frequently the highest of 500 waves will be 176 percent and highest of 1000 waves will be 186 percent of the significant wave height, (Pierson, op. cit.). A forecast of 10 ft might well include "occasionally 12 ft and rarely 17 to 19 ft." This would be a means of conveying the statistical distribution of waves the ship might experience over a period of time.

Consider first a stationary, circular tropical cyclone with uniform gradient of wind velocity inward toward a maximum in the wall cloud. Such a wind field produces a uniform circular ocean-wave pattern with far less variability than the wind field producing it. Increasing fetch length with increasing distance from the eye tends to compensate for the decrease in wind strength, thus reducing the gradient of wave heights that might be expected on the sole basis of wind speed.

The maximum fetch will not exceed 100 n mi for a stationary cyclone of radius 100 n mi (see Figure 7). This circumstance limits wave development for all winds over 21 kt. Significant wave heights increase inward from 10 ft at 70 n mi from the eye to 14 ft at 20 n mi from the eye. Under the wall cloud itself higher winds become the primary concern. Wave development under the wall cloud is severely limited by the small fetch distance and a decreasing probability that the storm track would be straight enough to keep the narrow wall-cloud zone above waves previously generated by winds of the wall cloud. There may be some increase above 14 ft in the last five n mi toward the radius of maximum wind, but probably not more than 3 or 4 ft. The compensation of increasing fetch for decreasing winds outward from the center results in a gradient of only about 3.5 ft in sea height over the 50 n mi distance from the outer edge of the wall cloud although the wind gradient was 38 kt over the same distance.

A moving cyclone increases the effective fetch in the direction of cyclone motion. Theoretically, waves whose group velocity is equal to the speed of cyclone motion will have unlimited fetch conditions. Since eastern Pacific Ocean cyclones move at speeds of 5 to 15 kt the largest wave period expected to develop fully would be 10 seconds (with a significant wave height of about 22 ft). Thus the movement of tropical systems is necessary to produce waves of dangerous size in the EASTROPAC latitudes and the size of possible waves is a function of cyclone radius, the maximum wind speed, the speed of motion of the cyclone and the track followed. The larger the cyclone, the higher the maximum wind, the faster the speed of translation and the straighter the track, the larger will be the generated wave forms.

A second factor limiting wave development is duration. Using the duration graphs from Pierson, Neumann and James (op. cit.) it can be shown that only four to nine hours are required to reach the fetch-limited wave heights postulated. Waves should develop nearly as fast as the wind system can expand and intensify. The response of the sea to changes in wind has only a short lag. Duration is generally not a limiting consideration. Further evidence of this may be found in empirical wave studies of tropical cyclones by Unoki (1960). He observed that the largest waves are found to the right of the axis of motion, but also noted considerable wave development in the left forward quadrant. A cyclone of radius 100 n mi advancing at 10 kt provides a

duration of easterly winds for the left front quadrant of 10 hr, enough to reach the fetch-limited wave heights of the example cyclone.

Pore (op. cit.) found that wave conditions do not change materially from day to day in mature hurricanes. This suggests that the factor of fetch may be most significant in limiting the wave energy spectra associated with tropical cyclones. As an example consider a model circular cyclone moving at a nominal 10-kt speed. There are two significant effects associated with this model. The first is the increase of the mean wind speed in the right semicircle and the accompanying decrease of the mean wind speed in the left semicircle in the amount of the speed of translation of the system. This produces a 20-kt differential in wind speed across the axis of motion and serves to significantly distort the generated wave pattern. Shea (1972) has documented supergradient winds 10 percent in excess of the speed of translation in the right semicircle. The second effect is the modification of both fetch and duration values so that they are increased to the right and decreased to the left of of axis of motion. The group velocity of waves is given (in knots) as 1.52T where T is the period in seconds, (Pierson, Neumann and James op. cit.). Thus a wave period of 6.7 seconds has a group velocity of 10 kt and would remain constantly under the region of generating winds in the right semicircle. This has the effect of removing fetch and duration limitations on the development of that portion of the

frequency spectrum "tuned" to the mean speed of translation of the tropical cyclone. Periods longer than 6.7 seconds are dispersive relative to the generating winds and soon move beyond the forward edge of the generating area. Periods less than 6.7 seconds similarly fall behind the rear-most edge. This dispersion of energy and the "escape" of longer-period waves reintroduce the limitation of duration to maximum wave development for those waves that travel beyond the generating area. A wave of 16-second period has a group velocity of 24.4 kt and escapes from the generating area at the rate of 14.4 kt. A nominal hurricane in the eastern Pacific Ocean has a radius of 30-kt winds of about 100 n mi. The length of the generating area of winds having a significant component along the axis of motion is about 100 n mi; so a wave with a period of 16 seconds, located in the rear of the generation area, will escape from the front of the area in about 6.9 hr. If the storm were stationary, however, the duration of influence of the storm on that wave would have been only 4.3 hr. Translation of the storm increases the duration limit by 59 percent in this example. A storm moving at a speed of 13 kt increases the duration limit by 105 percent to a value of 8.8 hr.

The energy of a wave is directly proportional to the square of wave height. A wave of initially insignificant height and a 16-second period located in the rear of the fetch will emerge from the front of the fetch with an increased significant height. In the stationary model the

wave height on exit will be 7.0 ft. From a similar cyclone moving at 13 kt the height reached will be 9.7 ft due to the increase in duration. Considering both the increased duration (8.8 hr) and the addition of the cyclone speed (13 kt) to the circulation velocity (30 kt) in the right hand semicircle the significant wave height will reach 15 ft.

Theoretically, seas encountered in crossing ahead of a cyclone moving at nominal speed on a straight track are likely to be considerably higher than those at the same distance from a stationary or slowly moving cyclone of the same intensity. In the above example seven-ft seas would not adversely affect the speed of most merchant vessels while 15-ft seas might slow forward motion to the point where a ship could be drawn into the dangerous wall cloud and suffer severe damage. The two possible outcomes in the above example depend not so much on the ability to forecast the wind field properly, but on the ability to interpret the effect of the wind field and storm motion on the generation of waves and to estimate the effect of sea conditions on the speed of particular ships.

The left semicircle of moving tropical cyclones influences a wave form for a shorter time since the cyclone moves opposite to the mean wind direction. Also the mean energy at the upwind edge of the generating area is not produced by the same storm. Energy of all wave lengths exists to the rear of the cyclone. Pore (op. cit.) in a study of reported wave conditions found that mean wave heights were indeed less in

the left semicircle than the right and less in the left front quadrant than in the left rear, consistent with the logic of movement presented here. Arakawa and Suda (1953) were referenced by Pore as presenting evidence that the longest swell occurred in the right rear quadrant. Pore's own study showed equal distribution between right forward and right rear quadrants. His study should be applied cautiously in the eastern Pacific area since the reports used extend 60 to 480 n mi from the centers of Atlantic hurricanes. He recorded only 19 reports of 7 plotted storm periods within 300 n mi of the cyclone centers. The usual maximum wave height reported within a 300 n mi radius was 13 ft. This was associated with winds of 30 kt at a mean distance of 170 n mi and 50 kt at a distance of less than 80 n mi.

In the eastern Pacific area formation occurs as near to shore as 120 n mi. The orientation of the western coastline of Mexico is roughly parallel to the normal west-by-northwesterly course of tropical cyclones in the belt of trade winds. The frictional influence of the Mexican coastline appears to limit expansion in size of these storms effectively except for those that move further offshore. Any intensification must occur without the normal areal expansion that accompanies a similar intensification in the less restricted waters of the Atlantic or western Pacific. The smaller mean diameter of EASTROPAC cyclones reduces the area of high seas to be expected in association with nominal

storms. Further, the smaller diameter restricts the maximum wave heights expected through reduction of the mean fetch. The relatively straight tracks of the usual eastern Pacific tropical cyclone encourages maximum wave development in the right semicircle. Any curvature of the track to the right or left should result in immediate reduction of sea state in the right semicircle. Acceleration of the cyclone along the track should result in higher maximum seas, since some long-period waves of greater growth potential, which would normally outrun the wind generating area, would now be overtaken and energy would be added. Winds of the right semicircle would be increased as a result of the acceleration and could thus result in a further increased sea state. Since there is a tendency of EASTROPAC cyclones to turn northward with increasing latitude (Figure 3), seas in the northern semicircle tend to be increased.

Sea states are not always reported by ships and the lower sea states reported may not have been noted in the annual summaries. Reporting of exceptional winds and sea states is more common. The following reports are taken from Mariners Weather Log, issues 1956-1971, and will be used to infer some basic relationships between EASTROPAC storms and their sea states. Reported sea states in Table XX are variable for a given reported wind speed. The variations can be explained by fetch limitation associated with varied size of cyclones, the position of the observing vessel in relation to storm motion, the speed of motion of the storm and the unknown

reliabilities of wind and sea reports. It may be noted that not enough reports have been collected to stratify reports according to parameters of storm size, intensity or motion. In a general sense however we find only nine reports (18 percent) with seas of 30 feet or more during 16 years of record. The most commonly reported sea states were 11 to 17 ft and 69 percent should be a conservative frequency for seas less than 17 ft. The data support the conclusion that the occurrence of exceptionally high sea states in EASTROPAC is of limited area and infrequent occurrence.

This fact suggests that avoidance of high seas by circumnavigation is a feasible procedure to consider. The speed of motion of EASTROPAC cyclones is 3 to 18 kt with the most commonly observed speed about 10 kt. This slow speed becomes a second factor toward favoring local maneuvering to avoid the cyclone. The third major circumstance aiding the mariner is the small size of the cyclone itself. A storm of 3.5 degrees latitude in diameter is larger than most EASTROPAC storms and yet has winds of gale force no more than 100 n mi from the center. Finally we note a more predictable behavior for the average EASTROPAC cyclone compared to Atlantic or WESTPAC tropical cyclones. By making full use of radar, published warnings and locally observed weather conditions it should be possible for ships to avoid winds of more than 35 kt and seas of more than 17 ft with only relatively minor adjustments of the route.

On the other hand, relatively rapid initial development of EASTROPAC cyclones is sometimes indicated. Many of the reports in the sample, even after the advent of satellite coverage, were reports used as a basis for issuing initial tropical storm warnings. Frequently cyclones reached full hurricane status within 48 hr of formation. Timely warnings of tropical cyclones in their initial stages are necessary to enable vessels to avoid damaging encounters with high winds and seas.

Literature and this author's analysis suggest the following empirical rules for forecasting sea states associated with EASTROPAC tropical cyclones:

1. The sea state has much less gradient than the wind field since decreased winds are compensated by increased fetch length at greater distance from the eye.
2. There is a quasi-discontinuous field of sea state with higher sea states in the right semicircle and lowest sea state in left rear quadrant.
3. Higher sea states are to be anticipated in the right semicircle of cyclones with a history of a straight track.
4. For straight running cyclones anticipate higher sea states when a cyclone accelerates and lower sea states when it decelerates.
5. Anticipate reductions of maximum sea state whenever curvature of the track is forecasted; however, curvature to the right strengthens the general wave field north of the center.

6. Forecast 120 percent of the significant-height forecast (for the highest one of 20)as "occasionally"observed and 180 percent of the significant height as "rarely" occurring (to be interpreted as once in a one to two-hour period.)
7. Anticipate maximum development of wave periods tuned to the speed of motion of the cyclone.
8. If the cyclone is moving in a straight line, 16 hours is a reasonable duration limit for waves moving through the generating area.
9. The average reported wave heights for EASTROPAC cyclones are considerably less than those normally associated with hurricanes.

XI. CONCLUSIONS AND MAJOR FINDINGS

The general approach used in this study hopefully provides a framework for further research in tropical cyclones of the eastern North Pacific Ocean area. Topics for further research, which have suggested themselves in the course of this study, are outlined in Section XII.

The major findings of this study emphasize the consistent nature and behavior of EASTROPAC cyclones.

1. The frequency of occurrence in this limited area and season is greater than that of any other area in the world. Annually 9.1 tropical storms and 5.4 hurricanes form between 15 May and 15 November.
2. The range of size in mean circular cloud diameter is from 1.5 to 5.5 degrees of latitude. The mean area of an EASTROPAC cyclone is about half the mean area of a WESTPAC cyclone.
3. The usual range of speed is from 5 to 18 kt with a mean of 10.3 kt and a standard deviation of 3.0 kt. A variation of speed with latitude is described..
4. The mean track direction is 292 degrees. A variation with latitude is described.
5. Recurvature occurs in 1.8 (15 percent) of the annual EASTROPAC cyclone tracks, primarily after 1 September.
6. The potential forecast error associated with recurvature is less in the EASTROPAC area than in the WESTPAC area because of lower frequencies of recurvature, a more

restricted season and area of recurvature, and typically lower speeds during and after recurvature.

7. Development and dissipation of EASTROPAC cyclones have been linked to sea-surface and sub-surface temperatures, anomalies of sea-level pressure and 700-mb heights of the central Pacific high and the vertical-shear pattern between the gradient and 250-mb levels.
8. Relationships between EASTROPAC, WESTPAC and Atlantic cyclogenesis have been described. The EASTROPAC seasonal frequency anomaly usually has the same sign as that of WESTPAC and the opposite sign of the Atlantic anomaly.
9. The mean temperature of the sea-surface at formation was shown to be 84.3F and the mean temperature at dissipation was 78.2F.
10. The frequency of intensification to hurricane force was shown to be less than that of WESTPAC but more than that of the Atlantic.
11. The ocean-wave field of a tropical cyclone is more uniform than the wind-field with respect to distance from the wall cloud. Wave development is limited primarily by the size of EASTROPAC tropical cyclones. At least 70 percent of gale-force or greater wind reports will have significant wave heights of less than 17 ft. The ability to forecast the EASTROPAC ocean-wave field accurately depends not so much on the ability to forecast a maximum wind as the ability to estimate the effective fetch as affected by cyclone size and movement.

12. EASTROPAC cyclones are relatively predictable in their nature and movement. Consistently accurate forecasts are possible on the basis of satellite data, daily aircraft reconnaissance, FNWC analyses and prognoses and the climatology developed in this study.

XII. SUGGESTED TOPICS FOR FURTHER STUDY

A. BURST CYCLOGENESIS

EASTROPAC cyclogenesis frequently occurs in bursts with two storms forming on the same day or only one day apart. The separation between these storms, the relationship of their strengths, sizes, speeds and paths is of interest to the operational forecaster.

Bursts of cyclogenesis have been observed to the extent that frequency of formation is far above expected levels for a short period.

In 1966, 5 cyclones formed between 5 and 14 September

In 1967, 4 cyclones formed between 5 and 13 September

In 1968, 5 cyclones formed between 21 and 28 August

In 1970, 5 cyclones formed between 14 and 29 July

Contrasting these periods are three periods of far-below-normal levels of activity. No storms formed between 30 June and 7 August 1965 or between 21 June and 31 July 1966. Only one storm formed between 6 September and 11 October 1970. Characteristic differences must exist which would further define the requirements of cyclogenesis.

B. TELECONNECTIONS OF ATLANTIC-EASTROPAC-WESTPAC CYCLOGENESIS

The spatial separation between quasi-simultaneous cyclogenesis in two major areas of cyclogenesis is postulated to be related to long-wave features of the atmosphere. Once the relationship is established, it may be used to predict

favorable and unfavorable areas for cyclogenesis. FNWC's pattern-separation fields may be suitable for research into this problem.

C. INTENSIFICATION OF EASTROPAC CYCLONES

It is postulated that the maximum development of EASTROPAC cyclones depends on time within the area favorable for cyclogenesis and the value of the positive temperature anomaly. Points of origin, lengths of track to the edge of the area and speeds of cyclones are arguments for estimating cyclone strength. The rate of intensification for tropical cyclones has been studied by Brand (1971) for the western Pacific. In the limited EASTROPAC region it may be possible, at the time of formation, to forecast the maximum intensity to be reached by a newly-formed tropical storm. The trend and rate of intensification for shorter time periods is a possible product of this study.

D. CHARACTERISTICS AND CLIMATOLOGY OF SMALL EASTROPAC CYCLONES

A deeper look into the frequency, area, intensity, duration and other characteristics of these cyclones may provide a better understanding of the scale and causes of cyclogenesis in the tropics.

E. FORECASTING OF RECURVATURE

The relation of Ocean Station November winds and pressure heights to the occurrence or non-occurrence of recurvature and the location of the point of recurvature appears

to be an area of fruitful research. Single station analysis of upper winds and use of satellite pictures may be used to separate the recurvature cases from the non-recurving cyclones on the basis of the existing upper air patterns. Other stations might be used in conjunction with November to correlate recurvature occurrence.

F. SEA-SURFACE TEMPERATURE AND CYCLOGENESIS

The sample of data used to estimate a surface temperature of 84.3F at the time of cyclogenesis was inadequate for high confidence. Additional years of data need to be considered to relate sea-surface temperatures to formation and dissipation. Repeated cyclogenesis in the same location over short periods should be studied.

G. FORECASTING WINTER GALE-FORCE WINDS IN THE GULF OF TEHUANTEPEC

An objective method of measuring the depth and speed of cold outbreaks moving south of Texas and New Mexico and timing the onset of resulting winds in the Gulf of Tehuantepec is needed for useful operational forecasts.

H. COMPOSITE ANALYSIS OF EASTROPAC CYCLONES

A complete compositing analysis of all available aircraft and surface data in the same manner as used by Shea (1972) will aid the definition of structure of the inner region of EASTROPAC cyclones. Ongoing research in this area at the masters thesis level will be completed in March 1973 at the Naval Postgraduate School.

I. CROSS EQUATORIAL TELECONNECTIONS AND EASTROPAC CYCLOGENESIS

Figure 17 shows a relationship between the two sides of the equator in cloud cover that is surprisingly consistent. Since there are no tropical cyclones in the eastern South Pacific the relationship must be of a larger scale or in some way independent of the occurrence of cyclogenesis. Separation of charts into extremes of above average cloudiness, below average cloudiness and intermediate cases might make it possible to identify the patterns associated with each type. Two thirds of the various band correlations computed by Allison (op. cit.) were $\geq$ .65 indicating a high probability of a real physical relationship across the equator.

TABLE I

ANNUAL FREQUENCY OF EASTROPAC CYCLOGENESIS

Year	TD*	TS	H	Warnings	Warning Days	Total TS-H
1945-1953						30
1954	*					10
1955	*					6
1956	*	6	5**	110		11
1957	*	2	7			9
1958	*	7	5	157		12
1959	*	9	3			12
1960	*	3	5			8
1961	*	9	2			11
1962	*	6	2	122	35	8
1963	*	5	4	80	26	9
1964	*	4	2	60	21	6
1965	2	9	1	244	73	10
1966	6	6	7	342	70	13
1967	2	12	6	474	119	18
1968	6	13	6	531	126	19
1969	5	6	4	219	67	10
1970	3	15	3	350	98	18
1971	3	3	11	410	89	14
Mean 1965-1971	3.9	9.1	5.4	367	92	14.6

* Prior to 1965, records were not kept on cyclones whose winds were < 34 knots.

**This is a very conservative evaluation. Two of the tropical storms had reported winds of 62 and 63 knots and probably were also of hurricane strength.

TABLE II

EASTROPAC TROPICAL CYCLOGENESIS BY SEMI-MONTHLY PERIODS WITHIN THE HURRICANE SEASON FOR ALL KNOWN CYCLONES 1921 - 1971

Period	Number	Percent	Cumulative Percent
May 16-31	4	2.0	2.0
Jun 1-15	12	6.2	8.2
Jun 16-30	14	7.2	15.4
Jul 1-15	21	10.8	26.2
Jul 16-31	23	11.8	38.0
Aug 1-15	18	9.2	47.2
Aug 16-31	24	12.3	59.5
Sep 1-15	33	16.9	76.4
Sep 16-30	17	8.7	85.2
Oct 1-15	13	6.7	91.8
Oct 16-31	15	7.7	99.5
Nov 1-15	1	0.5	100.00

TABLE III

EASTROPAC TROPICAL CYCLOGENESIS BY SEMI-MONTHLY PERIODS WITHIN THE HURRICANE SEASON (1965-1971)

Period	Number	Frequency	Percent	Cumulative %
May 16-31	2	0.3	1.9	1.9
Jun 1-15	5	0.7	4.8	6.7
Jun 16-30	9	1.3	8.6	15.2
Jul 1-15	11	1.6	10.5	25.7
Jul 16-31	12	1.7	11.4	37.2
Aug 1-15	10	1.4	9.5	46.7
Aug 16-31	17	2.4	16.2	62.9
Sep 1-15	17	2.4	16.2	79.1
Sep 16-30	6	0.9	5.7	84.8
Oct 1-15	9	1.3	8.6	93.3
Oct 16-31	6	0.9	5.7	99.0
Nov 1-15	1	0.1	1.0	100.00

TABLE IV

FREQUENCY BY MONTH AND DAY OF KNOWN EASTROPAC CYCLOGENESIS

DAY	MAY	JUN	JUL	AUG	SEP	OCT	NOV
1					4	3	1
2			4	1	3	1	
3		1	1	1	2	1	
4				4	2	3	
5		1	2	2	1	1	
6		1		2	3	1	
7		1	2	2	2		
8		1	3	2	5	1	
9		3	1		3		
10		1	2	1	2		1
11				2	1		
12		2	1	1	3	1	
13			1		3		
14		2	5		1	3	
15		1	3		2		
16		1	2	4		1	
17	1	1	2	2	2	2	
18		2	1		1	2	
19		1	3	2			
20		1	2	3	2	2	
21	1	2	5	2	3	2	
22		1	2	2		3	
23			2	2	2		
24		1			1		
25			1	1	2		
26		1	3	1	2	1	
27		1			1	1	
28		2	1	5	1	1	
29	1	1	1	2	1	1	
30			2		1		
31	1		1				
1921-1971 Total	4	29	53	44	56	31	2
1956-1971 Total	4	26	47	41	42	25	2

TABLE V

FREQUENCY OF TROPICAL CYCLONES $\geq$ 34 KT EASTROPAC VS WESTPAC

Year	WESTPAC	EASTROPAC	Ratio	%Chg(W)	%Chg(E)
1965	25	10	.40		
1966	26	13	.50	.04	.30
1967	28	18	.64	.08	.26
1968	24	19	.79	-.14	.06
1969	14	10	.71	-.44	-.47
1970	21	18	.86	.50	.80
1971	35	22	.63	.67	.22

TABLE VI

FREQUENCY OF TROPICAL CYCLONES $\geq$ 34 KT EASTROPAC VS ATLANTIC

Year	LANT	EASTROPAC	Ratio	%Chg(L)	%Chg(E)
1965	5	10	2.0		
1966	12	13	1.1	1.3	.30
1967	8	18	2.3	-.33	.26
1968	7	19	2.7	-.13	.06
1969	13	10	0.8	.86	-.47
1970	7	18	2.6	-.46	.80
1971	12	22	1.8	.72	.22

TABLE VII

MEAN DURATION IN DAYS OF EASTROPAC TROPICAL CYCLONES

Month	1956-1964	1965-1971*
June	4.1	4.5
July	4.7	7.0
August	6.1	6.8
September	5.0	7.0
October	3.5	6.5
Season	4.8	6.6

*The years with satellite data have been computed separately.

TABLE VIII

SEASONAL DISTRIBUTION OF EASTROPAC TROPICAL-CYCLONE DURATION 1965-1971

Duration	Jun	Jul	Aug	Sep	Oct	Season
1	0	1	0	0	1	2
2	0	2	1	3	3	9
3	7	3	4	2	3	19
4	3	5	3	6	4	21
5	1	4	1	8	2	16
6	0	3	1	2	0	6
7	1	2	0	2	1	6
8	0	0	0	1	0	1
9	1	2	0	0	0	3
10	0	0	1	1	0	2
11	0	0	1	1	0	2
12	0	0	1	0	0	1
13	0	0	0	0	0	0
14	0	0	0	0	0	0
15	0	0	0	0	0	0
Total	13	22	14	26	14	89
Mean (days)	4.5	7.0	6.8	7.0	6.5	6.6

TABLE IX

TROPICAL-CYCLONE CIRCULAR CLOUD DIAMETERS

Sample	Range	Mean(degrees Lat)	STD. DEV.
40 EASTROPAC cyclones	1.5-5.0	3.3	0.5
24 WESTPAC cyclones	2.7-7.2	4.7	1.0
*22 WESTPAC cyclones			0.6

*Gloria (1969) and Joan (1970) were excluded from this sample. Their respective diameters of 6.5 and 7.2 degrees place them in a category of cyclones not found in EASTROPAC.

TABLE X

MAXIMUM SPEEDS OF EASTROPAC HURRICANES 1965-1971*

Knots	Storms
5-5.9	1
6-6.9	
7-7.9	
8-8.9	
9-9.9	1
10-10.9	2
11-11.9	5
12-12.9	8
13-13.9	5
14-14.9	3
15-15.9	5
16-16.9	3
17-17.9	
18-18.9	3

Range	5.7 - 18.0
Mean	13.3
S.D.	2.6

Disregarding the 5.7 value as uncharacteristic:

Range	9.5 - 18.0
Mean	13.4
S.D.	2.3

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*The maximum mean speed evaluated over a 12- to 24-hour track segment.

TABLE XI

SPEED DETERMINATION ERRORS
USING
VARYING QUALITY FIX DATA

Method	Intensity	Accuracy	Intervals Speed Error and Equivalent 24-hr Distance							
			6 hr		12 hr		18 hr		24 hr	
		n mi	kt	n mi	kt	n mi	kt	n mi	kt	n mi
Aircraft	≥ 60kt	7.5*	2.5	60	1.3	30	0.8	20	0.6	15
Aircraft	< 60kt	9.5*	3.2	77	1.6	38	1.1	26	0.8	19
Satellite	60kt with good eye	11.9	6.6	158	3.3	79	2.2	53	1.6	39
Satellite	No eye visible	35.5	11.8	283	5.9	142	3.9	94	2.9	71

*Use given aircraft fix accuracy if it is a larger number than appears for that storm category.

TABLE XII

MEAN DIRECTION AND SPEED OF EASTROPAC CYCLONES BY FIVE-DEGREE LATITUDE/LONGITUDE BLOCKS

Block*	Mean Direction	Mean Speed	Number of Cyclones	Adjusted Speed**
10N90W	295	5.0	1	
10N95W	284	10.1	4	12.0
10N100W	289	10.5	8	11.8
10N105W	291	11.4	15	14.3
10N110W	272	11.2	11	12.2
10N115W	285	10.9	14	11.7
10N120W	274	9.3	6	9.3
10N125W	273	10.0	4	10.0
10N130W	273	11.9	2	11.9
10N135W	277	10.3	3	10.3
10N140W	290	14.0	1	14.0
15N100W	310	16.0	1	16.0
15N105W	306	10.3	11	10.1
15N110W	307	10.9	21	10.9
15N115W	302	10.4	19	10.4
15N120W	295	11.3	16	11.0
15N125W	289	12.2	13	12.2
15N130W	280	11.0	11	11.0
15N135W	283	10.5	6	10.5
15N140W	283	9.6	5	9.6
20N110W	340	10.3	6	10.3
20N115W	323	9.8	12	9.8
20N120W	302	10.8	6	10.8
20N125W	313	11.4	8	11.4
20N130W	309	9.3	9	9.3
20N135W	280	13.8	3	13.8
20N140W			0	
25N115W	355	7.1	3	7.1
25N120W	350	8.5	3	8.5
25N125W	040	10.0	1	10.0
25N130W			0	
25N135W	285	11.0	1	11.0
25N140W	285	4.0	1	4.0
Whole area	298	10.3		

* Five degree blocks are identified by the coordinates of the southwest corner.

**An adjusted speed is computed by eliminating the track segments of storms originating in the block. It represents the speed of crossing storms not originating within the block.

TABLE XIII

FREQUENCY, BY YEAR, OF RECURVING EASTROPAC CYCLONES (1956 - 1971)

Year	Cyclones	Recurved Number	Recurved Percentage
1956	11	0	0
1957	9	3	33
1958	12	2	17
1959	12	1	8
1960	8	0	0
1961	11	1	9
1962	8	1	12
1963	8	2	25
1964	6	0	0
1965	10	1	10
1966	13	4	31
1967	18	4	22
1968	19	2	11
1969	10	2	20
1970	18	1	5
1971	18	3	17
Mean	188	1.9	16

TABLE XIV

EASTROPAC VS WESTPAC
RECURVING TRACK SUMMARY
(1956-1971)

Frequency by periods within the storm season

		EASTROPAC		WESTPAC
Period	Cyclones	Recurved	Percentage	Percentage Recurved
May 15-31	4	0	0	58
Jun 1-15	13	1	8	35
Jun 16-30	13	1	8	35
Jul 1-15	22	0	0	20
Jul 16-31	25	0	0	19
Aug 1-15	15	0	0	30
Aug 16-31	25	0	0	39
Sep 1-15	28	6	21	46
Sep 16-30	14	5	36	42
Oct 1-15	13	7	54	54
Oct 16-31	14	6	43	56
Nov 1-15	2	2	100	56
	28			

TABLE XV

MOVEMENT OF RECURVING EASTPAC TROPICAL CYCLONES

DATE	PRE-RECURVATURE MEAN SPEED (KT)	ACCEL	POST-RECURVATURE SPEED CHANGE	ACCEL	DIR(DEG) TOWARD	SPEED (KT) MEAN	MAX
10/ 2/57	7.0	?	+	A	040	10.5	10.5
10/19/57	11.0	D	+	A	012	15.5	16.5
10/20/57		?	?	D	033	7.5	8.5
6 /13/58	3.0	D	+	A	035	6.5	7.5
10/29/58		?	?	?	011	13.5	13.5
10/26/59	6.0	D	0	?	060	6.0	6.0
11/10/61	7.0	?	+	A	058	9.0	10.0
10/ 4/62	11.2	A	+	A	025	18.5	20.0
9 /27/63	8	D	-	A	049	4	5.5
10/17/63		?	?	?	029	?	?
9 /24/65	3.5	?	+	0	040	7.5	7.5
6 /23/66	4.5	0	-	?	024	4.0	4.0
9 /12/66	7.0	A	+	D	071	7.0	9.5
9 /13/66	10	D	-	0	045	7.5	7.5
9 /26/66		?	?	?	037	?	?
9 /26/67	9.0	?	+	?	042	10.0	10.0
9 /13/67	10.5	?	+	?	060	12.5	12.5
9 /13/67	7.8	D	+	A	085	11.2	12.5
10/ 5/67	5.5	D	-	0	022	3.0	3.0
9 /11/68	6.0	0	+	0	058	7.0	7.0
10/ 1/68	6.8	D	+	A	028	5.8	6.5
10/ 1/69	6.8	A	+	0	064	8.5	8.5
10/10/69	8.5	D	-	0	022	7.5	7.5
9 / 4/70	11.2	D	-	D	029	4.0	5.5
11/ 2/70	8.5	D	-	A	033	6.0	6.5
9 /29/71	4.5	D	0	?	019	4.5	4.5
10/10/71	10.8	A	0	D	022	11	12.0
10/30/71		?	?	D	054	6.0	6.0
The "Classic" Recurver		D	+	A	-	-	-
Mean Values	7.6	(D)12/18	12/23	(A)9/20		8.2	8.8
		(A) 4/18	7/23	(D)5/20			

TABLE XVI

EASTROPAC RECURVING CYCLONES:SPEED BY DIRECTION OF TRACK AFTER RECURVATURE

Direction	Frequency	Mean Speed(kt)
001-019	3	11.2
020-029	7	7.7
030-039	3	6.7
040-049	5	7.9
050-059	3	8.0
060-090	5	9.0

TABLE XVII

MEAN STORM TRACKS AND RECURVATURE ANGLE AS A FUNCTION OF INITIAL TRACK DIRECTION

Initial Track	Sample	Mean Recurvature Angle*
270 - 279	1	35
280 - 289	5	45
290 - 299	4	79
300 - 309	7	83
310 - 319	3	98
320 - 329	2	110
330 - 339	2	118
340 - 349	1	126

Total recurving storms	28	
Number struck land	20	71%
Number died at sea	8	29%

Storm tracks	Mean(deg.)	STD.DEV.(deg.)
Before recurvature	302	17.1
After recurvature	040	17.4
Sharpness of Recurvature	81	29.2

*The interior angle between initial and final mean-track segments of recurving storms.

TABLE XVIII

MEAN LOCATION OF EASTROPAC CYCLONE RECURVATURE

MONTH	TOTAL CYCLONES	NUMBER RECURVED	PERCENT RECURVED	MEAN POSIT. OF RECURVATURE	STD.DEV. (LAT/LON)
May	4	0	0		
June	26	2	8	18.4N 107.6W	
July	47	0	0		
Aug	40	0	0		
Sep	42	11	26	21.0N 116.8W	2.2/7.9
Oct	27	13	48	18.6N 110.3W	2.3/4.0
Nov	2	2	100	16.0N 108.3W	
Season	188	28	15	19.3N 112.7W	2.6/6.7

TABLE XIX

Frequencies of Cyclogenesis and Anomalies of
Mean Monthly Sea-Surface Temperature over the
EASTROPAC Formative Region in 1970

Month	May	Jun	Jul	Aug	Sep	Oct	Nov
Climatology	.29	2.00	3.29	3.86	3.29	2.15	.14
Anomaly (F)	?	+2	+1	+1	-1.6	+1.3	0
Observations	1*	3	6	4	1	3	0

*Cyclogenesis on 30 May possibly should be included in the June column.

TABLE XX

REPORTED SEA STATE VS WIND SPEED IN EASTROPAC CYCLONES 1956-1971

Wind	Moderate	Rough*		Very Rough		High		Very High	Phenomenal
	8	8-13	13	13-20	20	20-30	30	30-45	45
25	1								
30		1		1					
35		1		2	1	1			
40	1	3	1	1	1		1		
45		2	1	3					
50		2	1	6	1	2			
55			1						
60		2				3			
65							1		
70					1		1	1	
75				1					
80								1	
85								1	1
90						1			
95							1		
100									
105									
110									1
Totals	2	11	4	14	4	7	4	3	2

*Seas were often reported as a range e.g., moderate to rough, or very rough to high. They were then recorded in feet at the median value. The sources of these reports are the annual summaries of eastern North Pacific tropical cyclones published in the _Mariners Weather Log_.

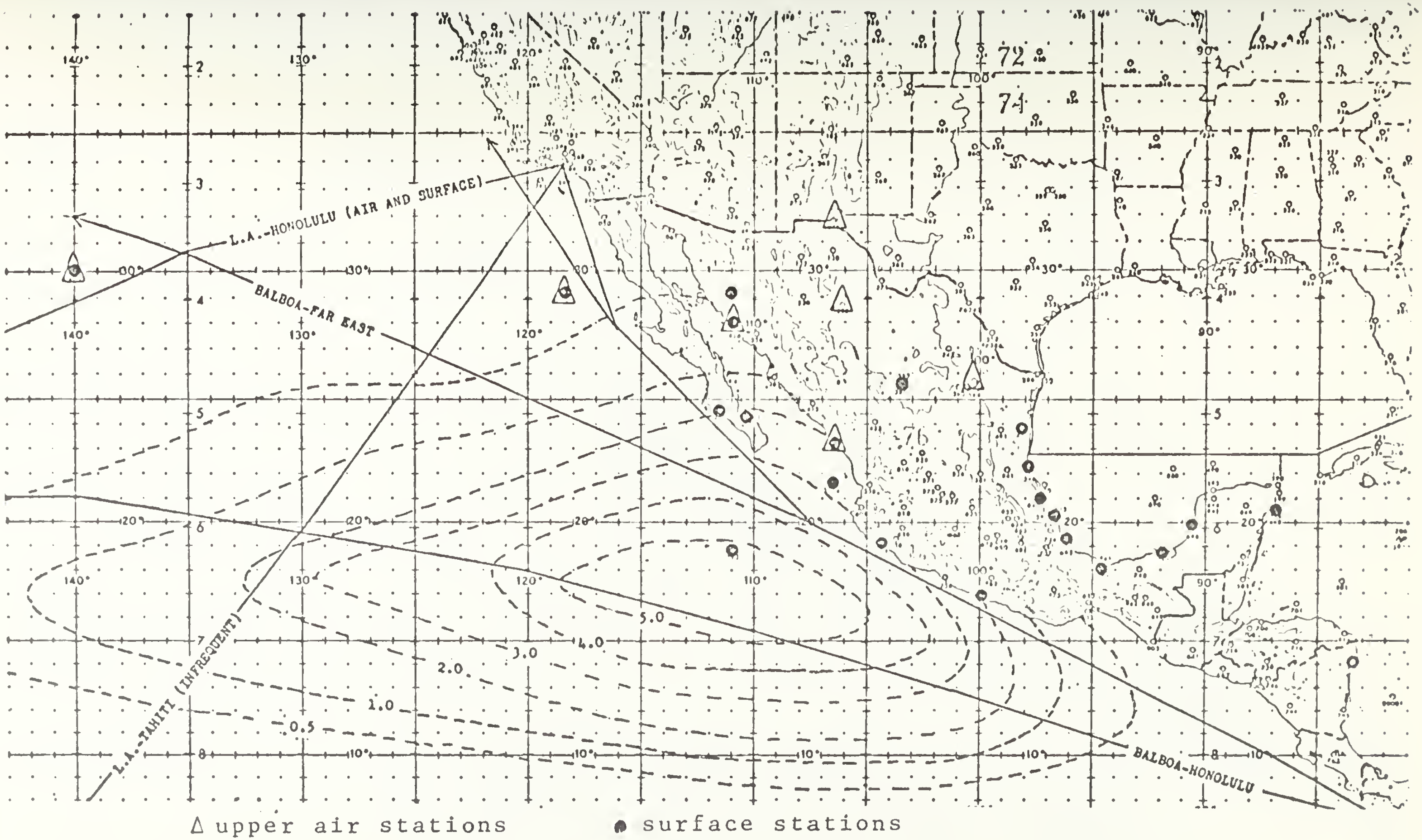


Figure 1. EASTROPAC observation network with major shipping and air traffic routes. The annual tropical cyclone crossing frequencies (---) are after Thom (1972).

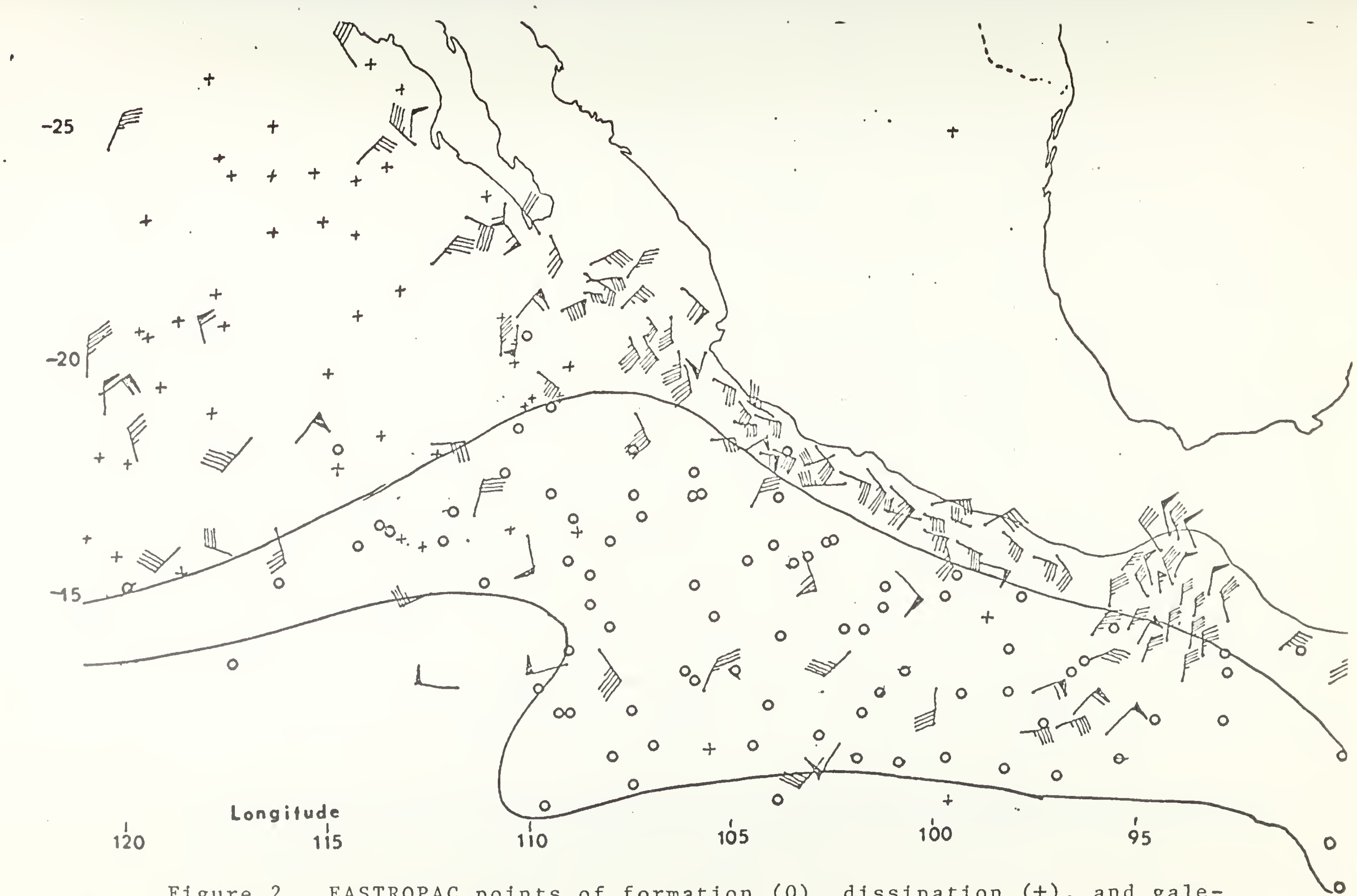


Figure 2. EASTROPAC points of formation (0), dissipation (+), and gale-force wind encounters.

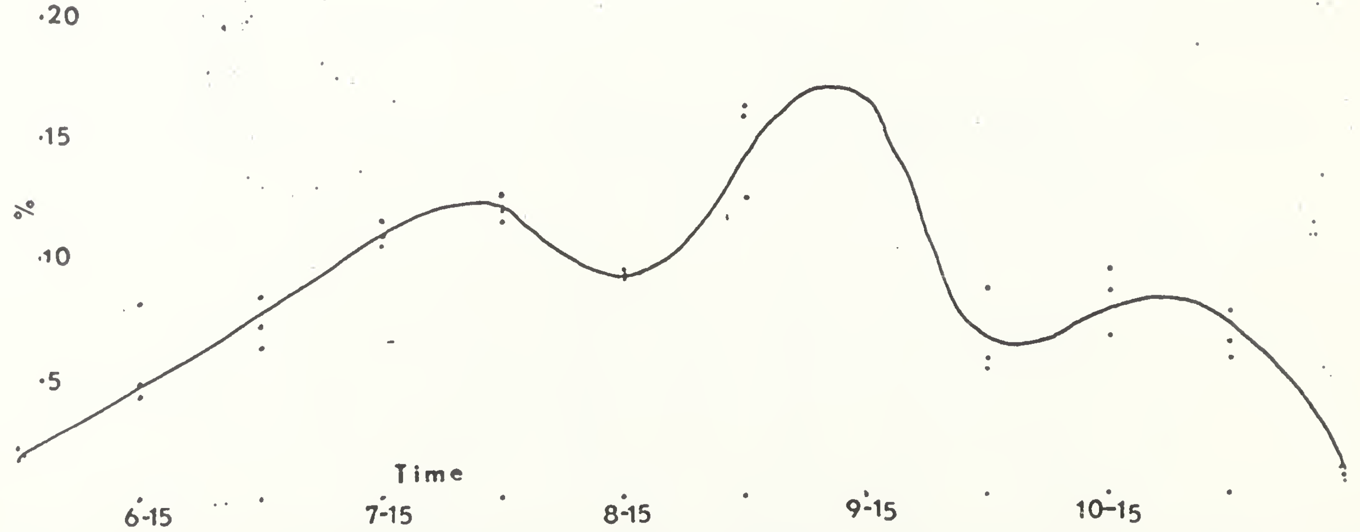


Figure 3. Frequency distribution of EASTROPAC cyclogenesis for 195 cases from 1921-1971, by 15 day intervals centered on first and fifteenth of each month.

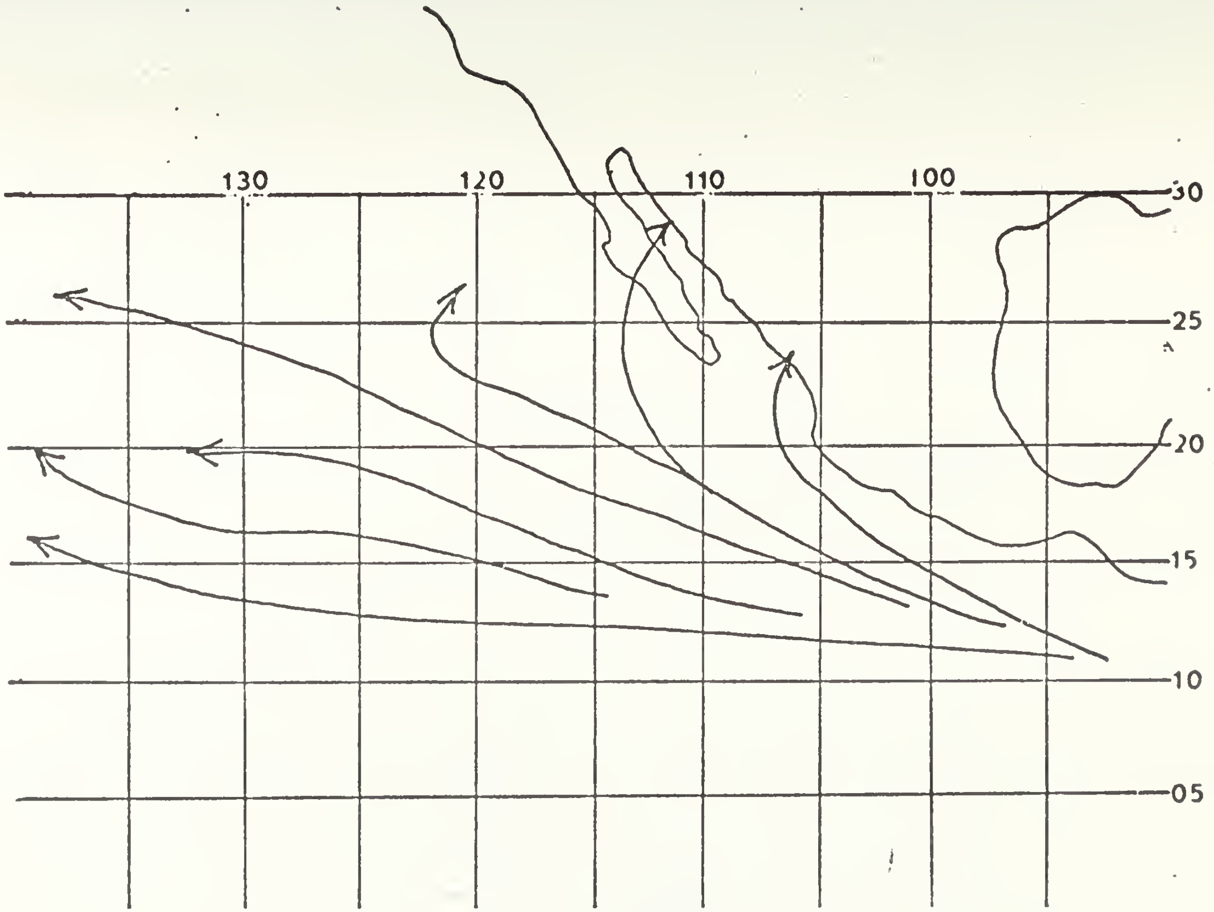


Figure 4. Mean EASTROPAC cyclone trajectories (based on five-degree squares).

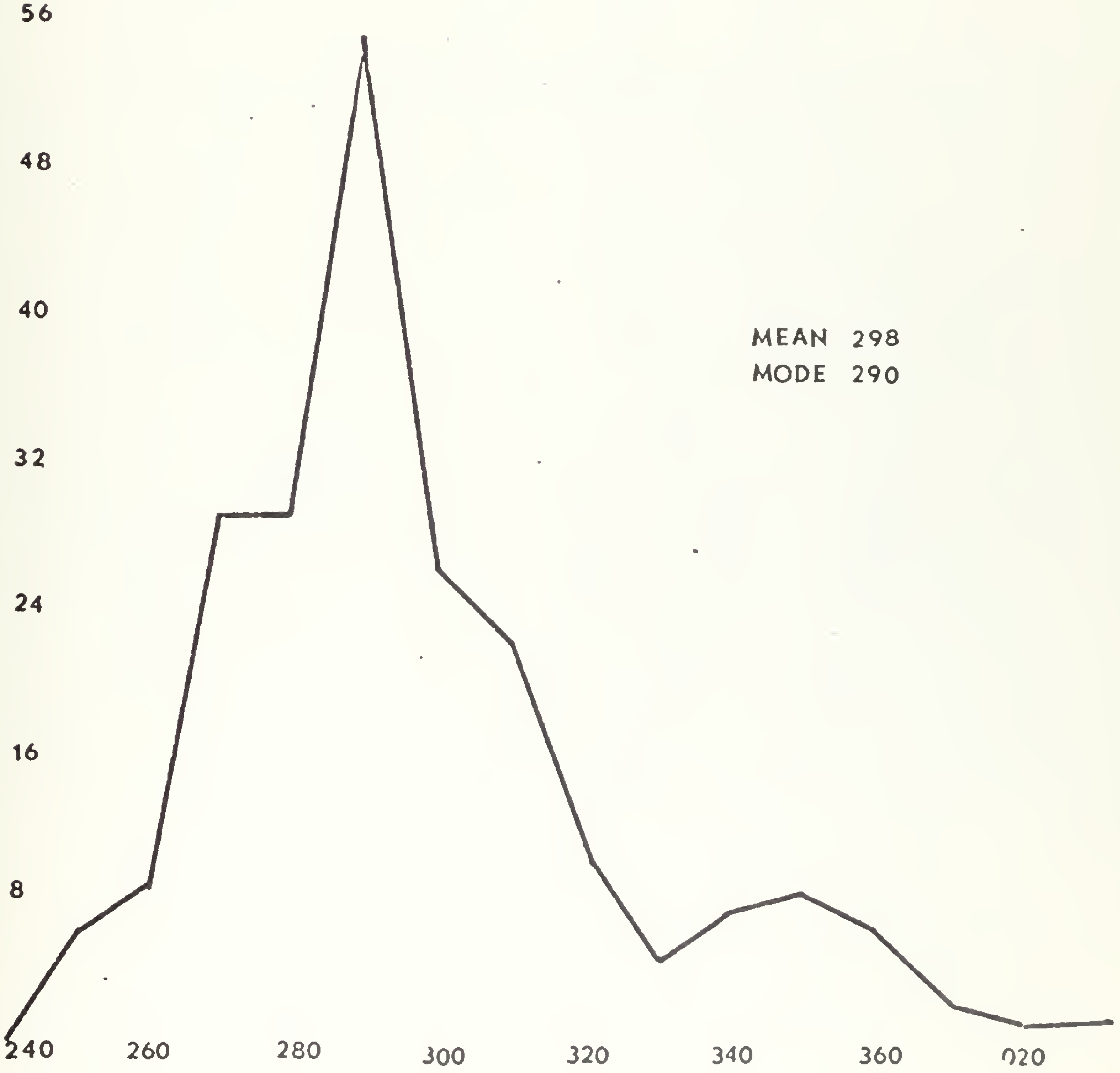


Figure 5. Frequency distribution of track direction.

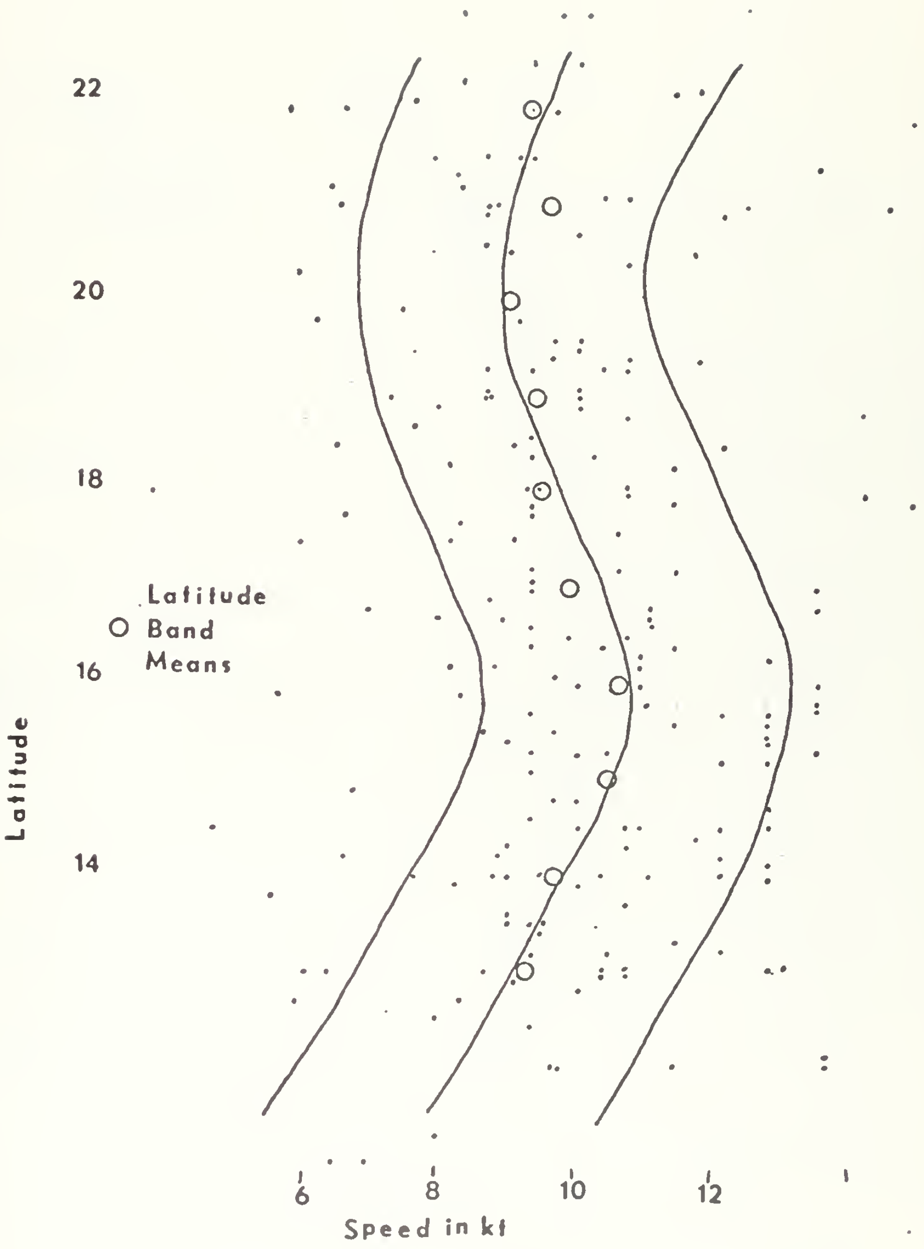


Figure 6. Variation of cyclone speed with latitude.

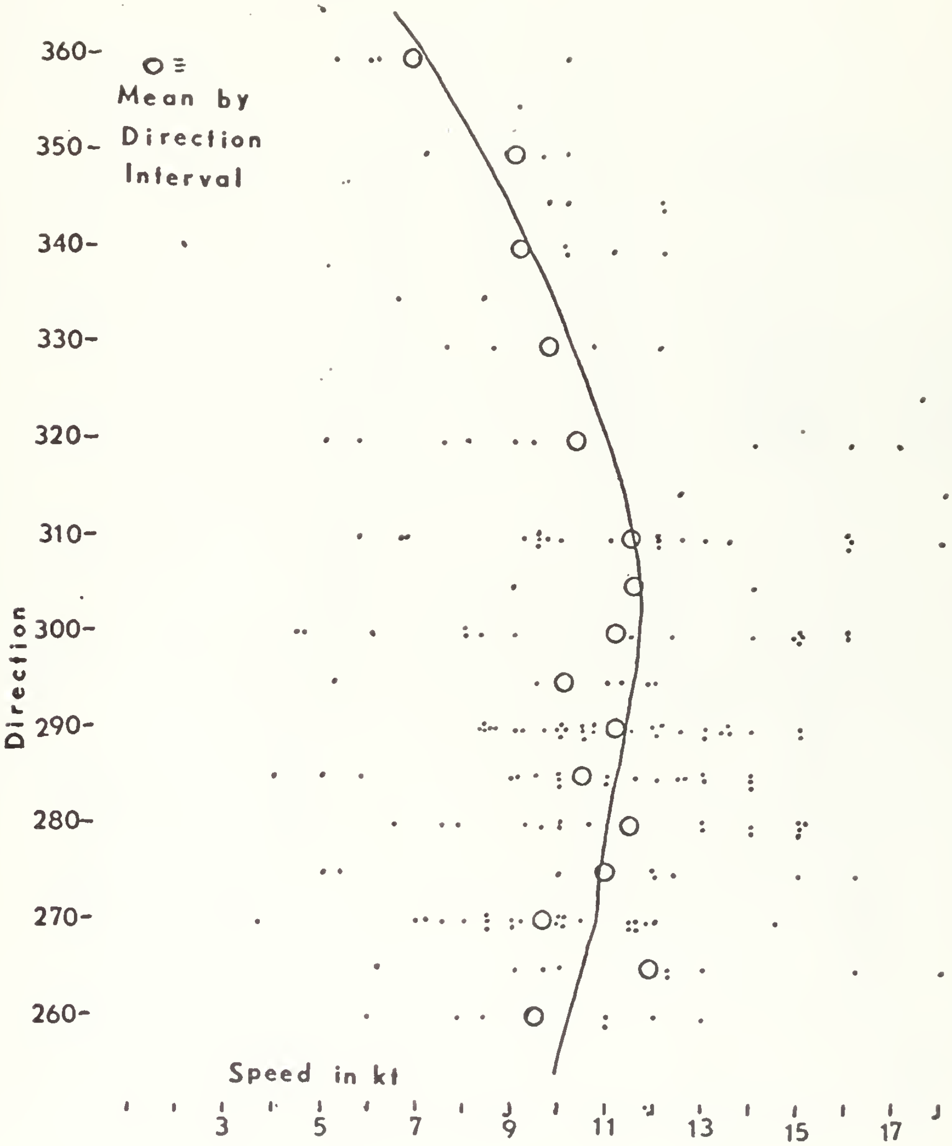


Figure 7. Variation of cyclone speed(s) with track direction.

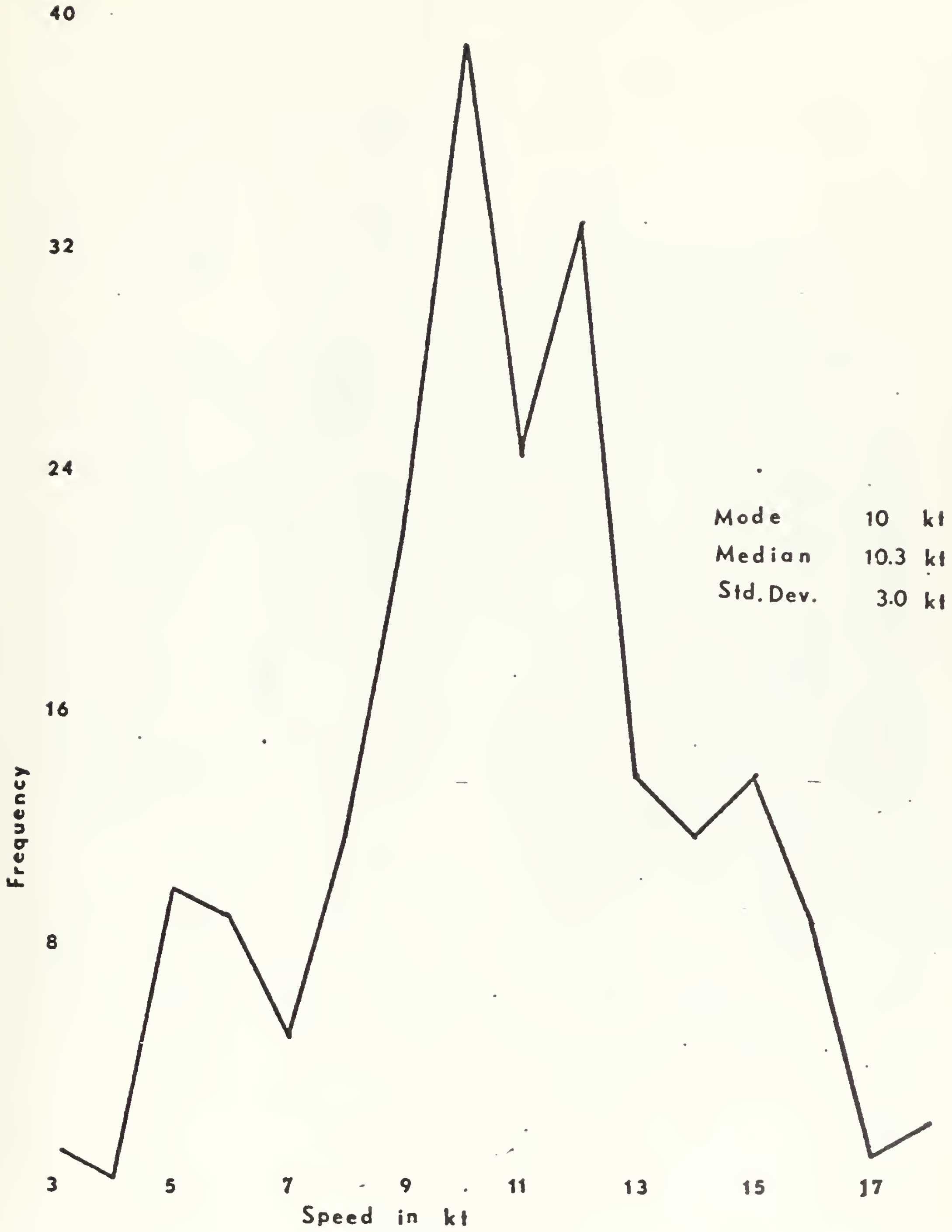


Figure 8. Frequency distribution of cyclone speed.

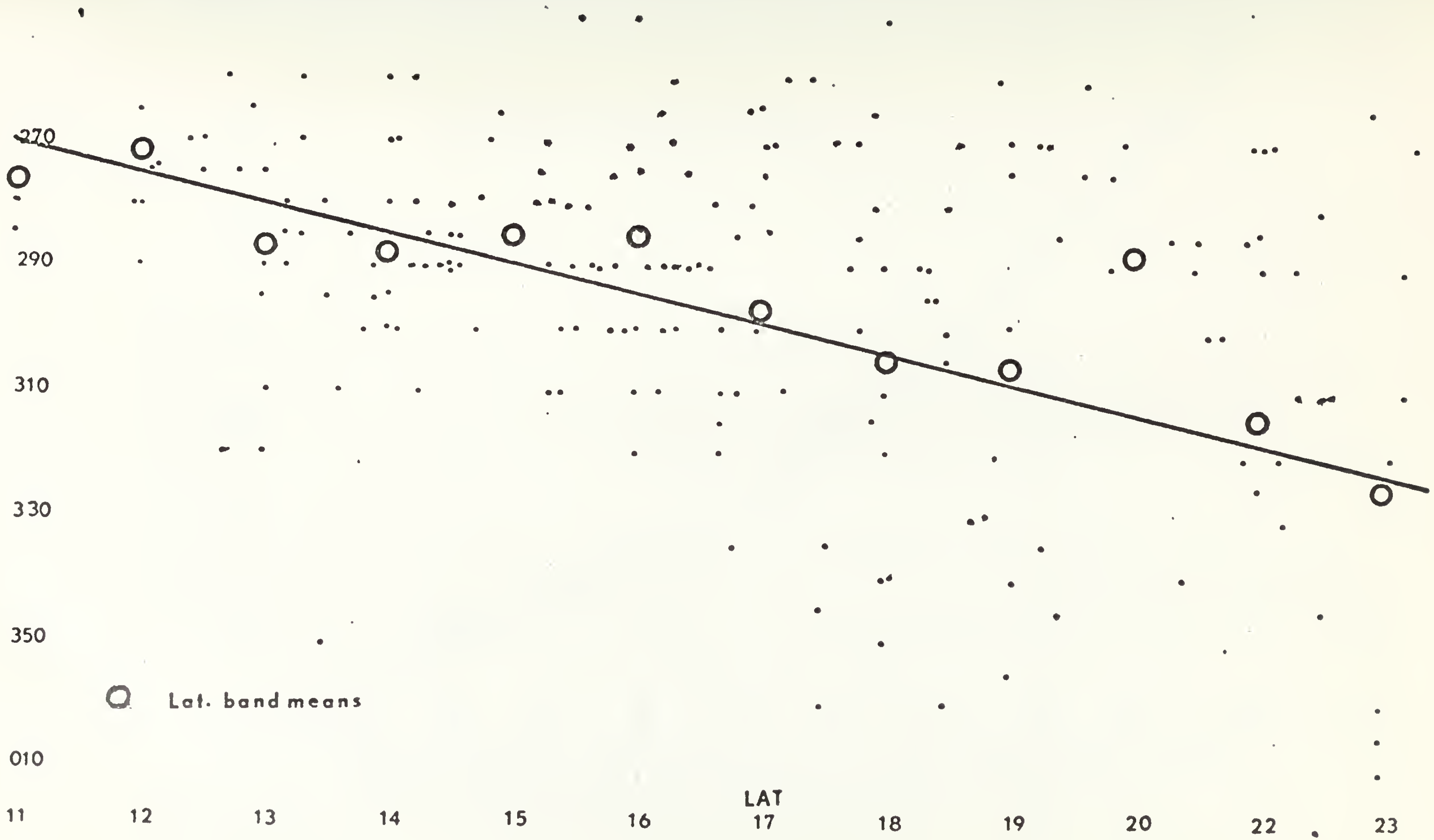


Figure 9. Variation of track direction with latitude.

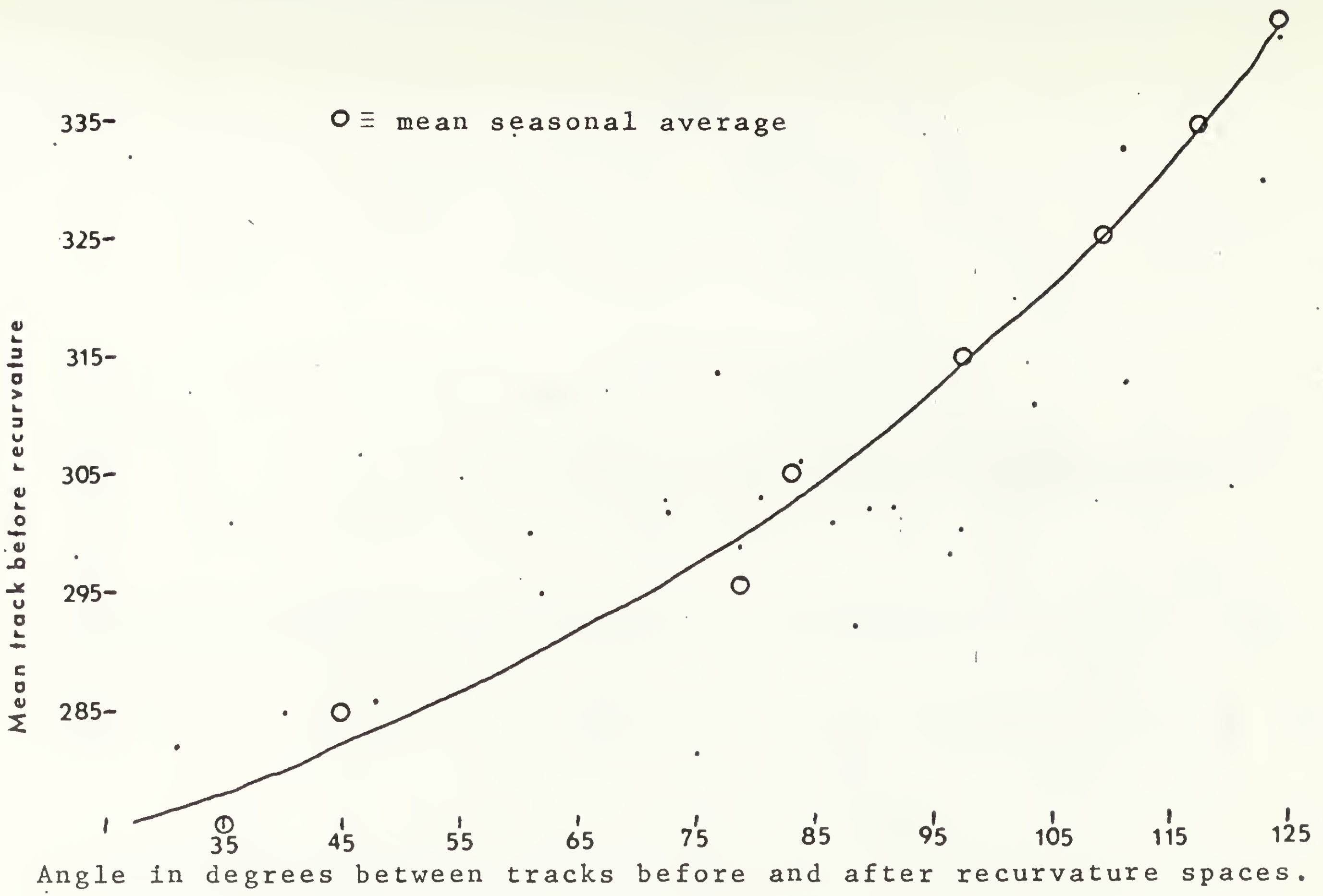
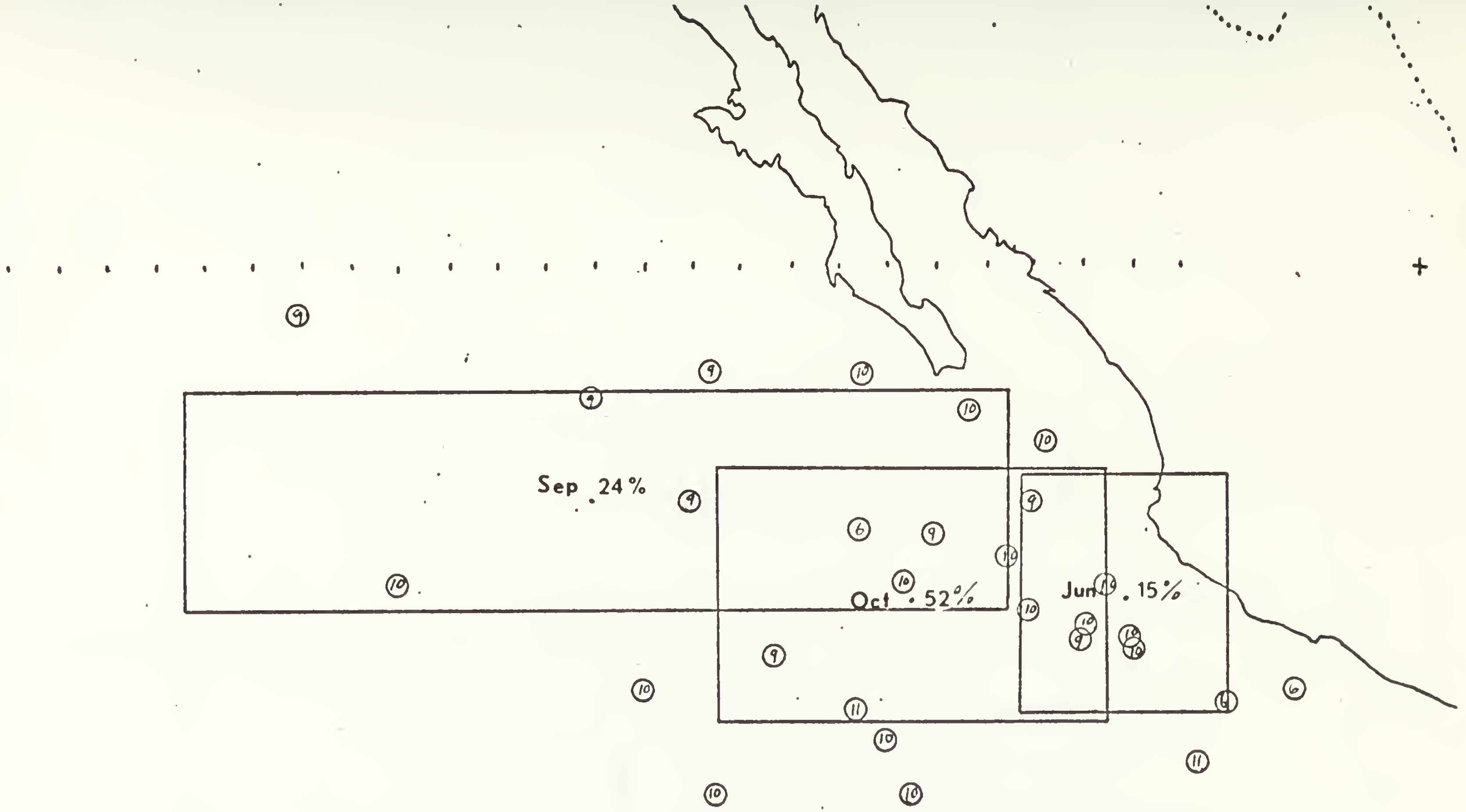


Figure 10. Relation of track after recurvature with track prior to recurvature.



Numbers in circles represent month of occurrence.

Figure 11. Points of recurvature of 28 EASTROPAC cyclones, 1956-1971. (Rectangular areas represent ± 1 std. dev. of latitude and longitude for each month.)

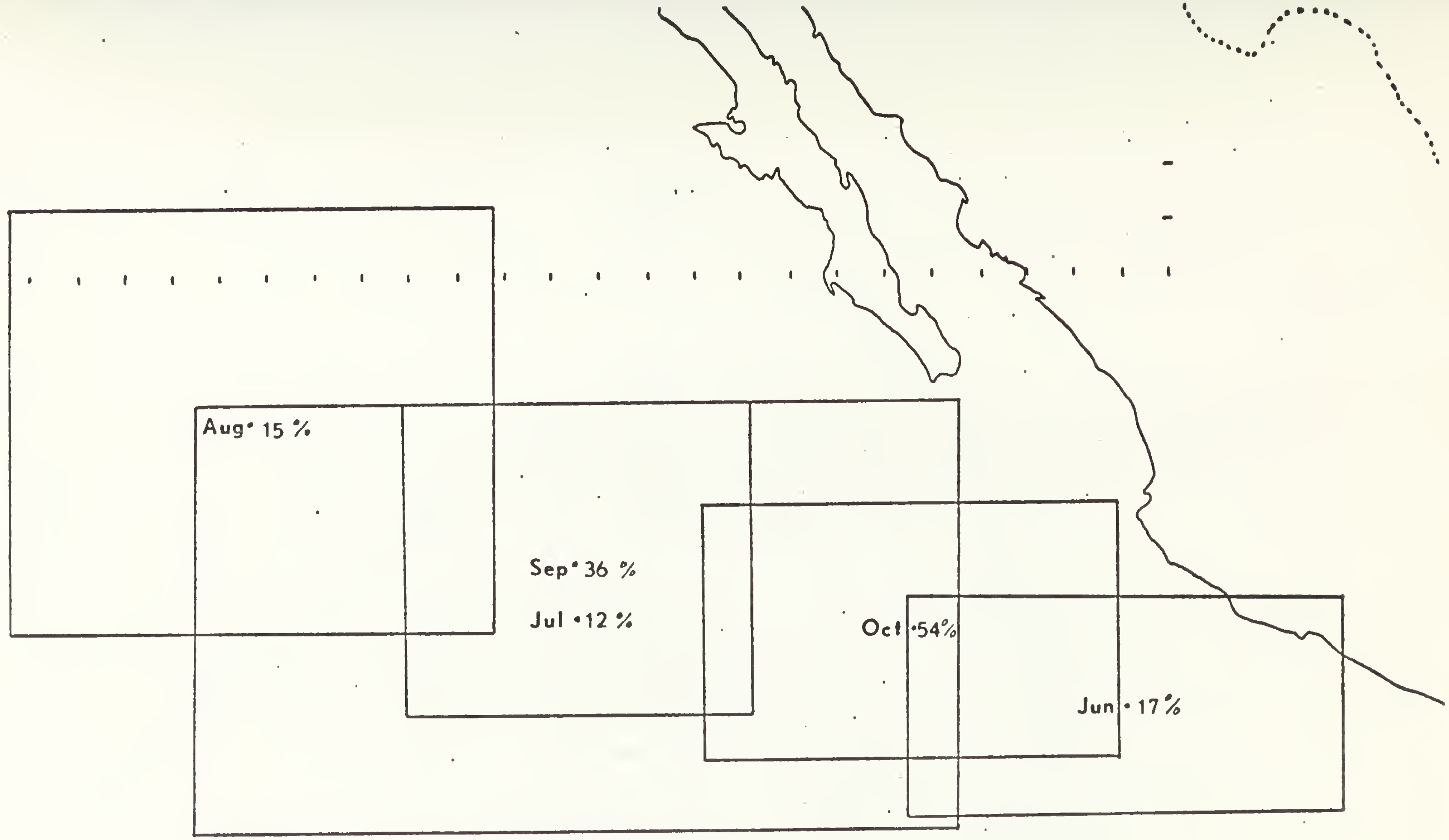


Figure 12. Points of inflection of EASTROPAC cyclones (right-breaking tracks). (Rectangular areas represent ± 1 std. dev. of latitude and longitude for each month.)

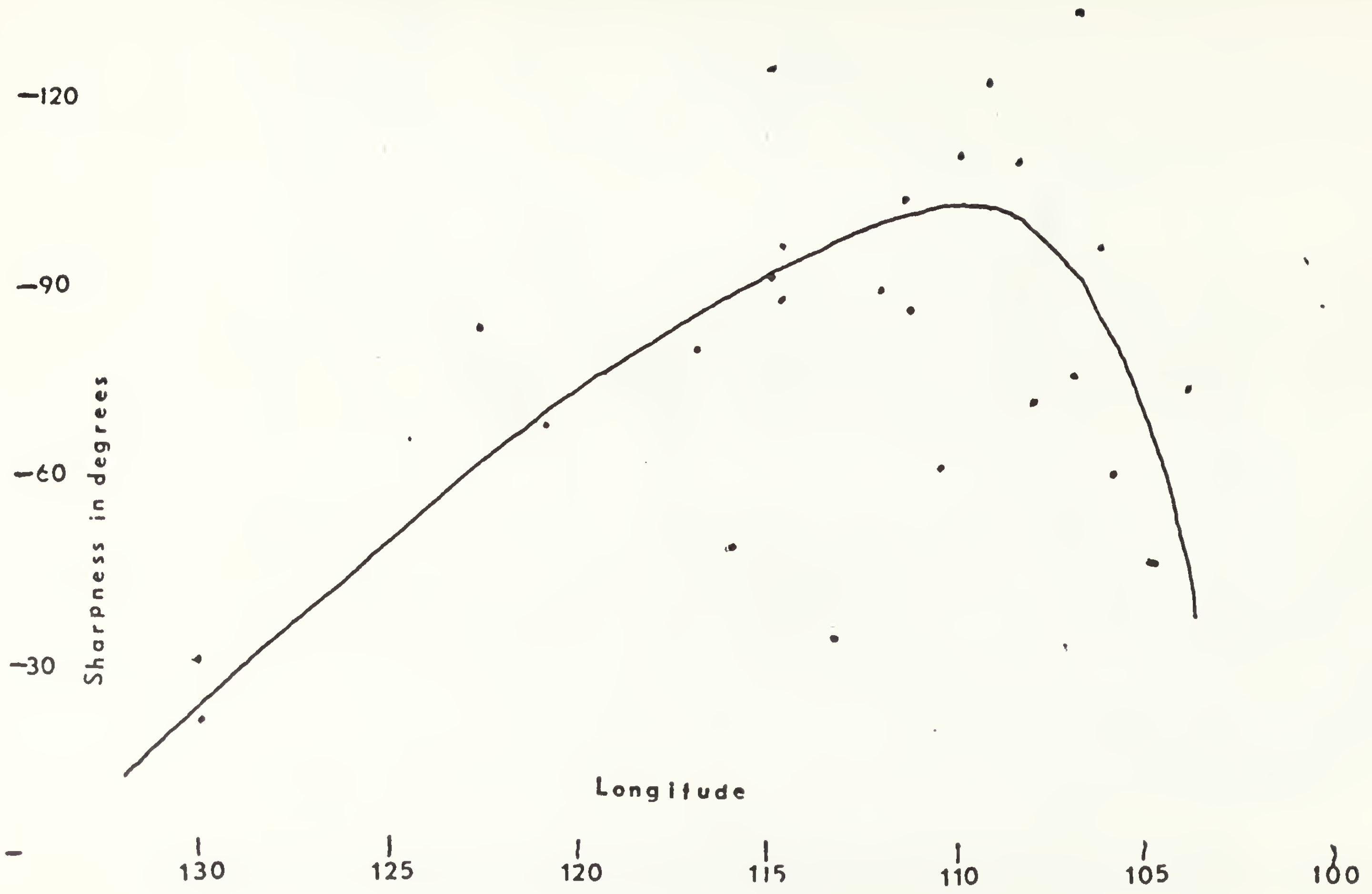


Figure 13. Relation of recurvature sharpness with longitude of recurvature.

Figure 14. Tropical cyclones crossing the Pacific coastline of Mexico, 1921-1971.

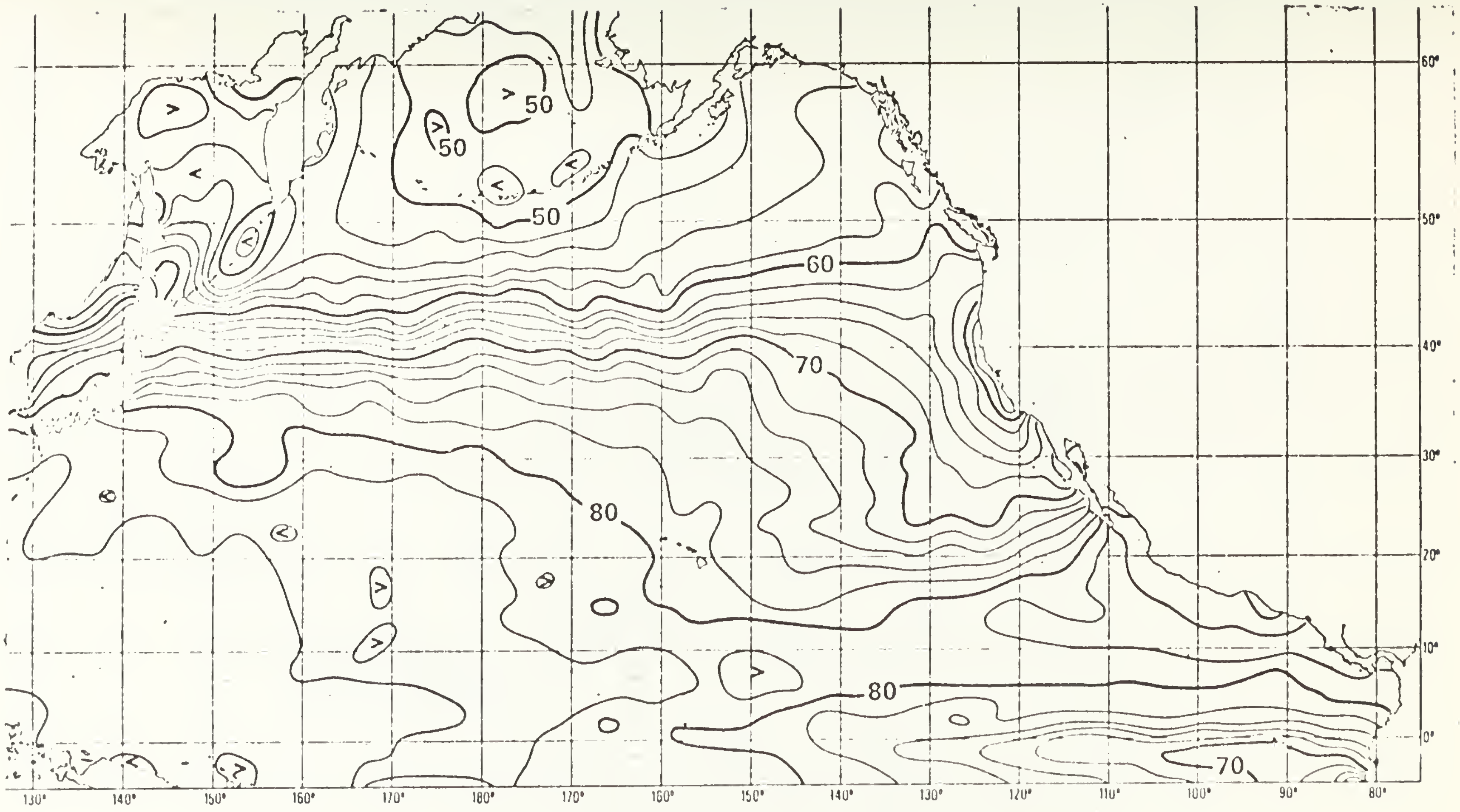


Figure 15. August mean sea-surface temperatures (^{o}F).

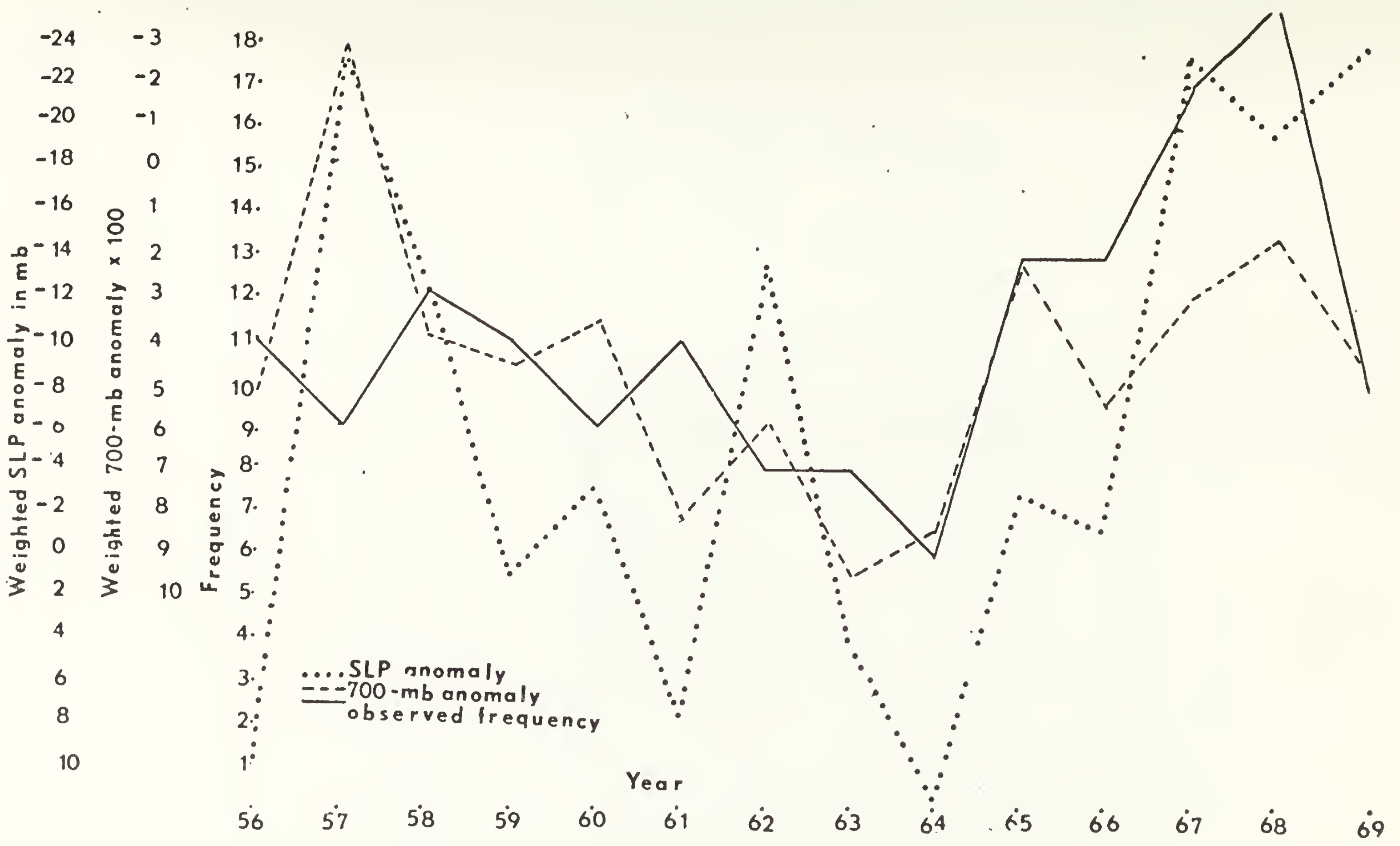


Figure 16. Central Pacific sea-level pressure and 700-mb height anomalies related to frequency of EASTROPAC cyclogenesis. Monthly anomalies from May through November are weighted by the expected frequency of cyclogenesis and totaled for the seasonal anomaly.

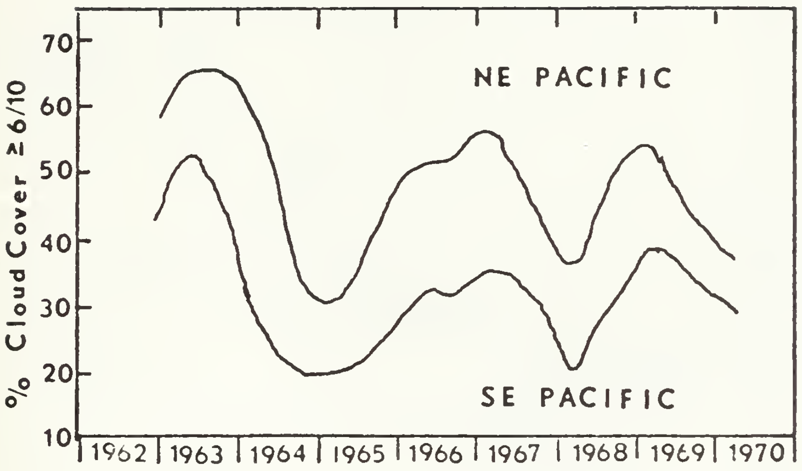


Figure 17. Relation of Eastern Pacific cloudiness in the Northern and Southern Hemispheres (after Allison, 1971).

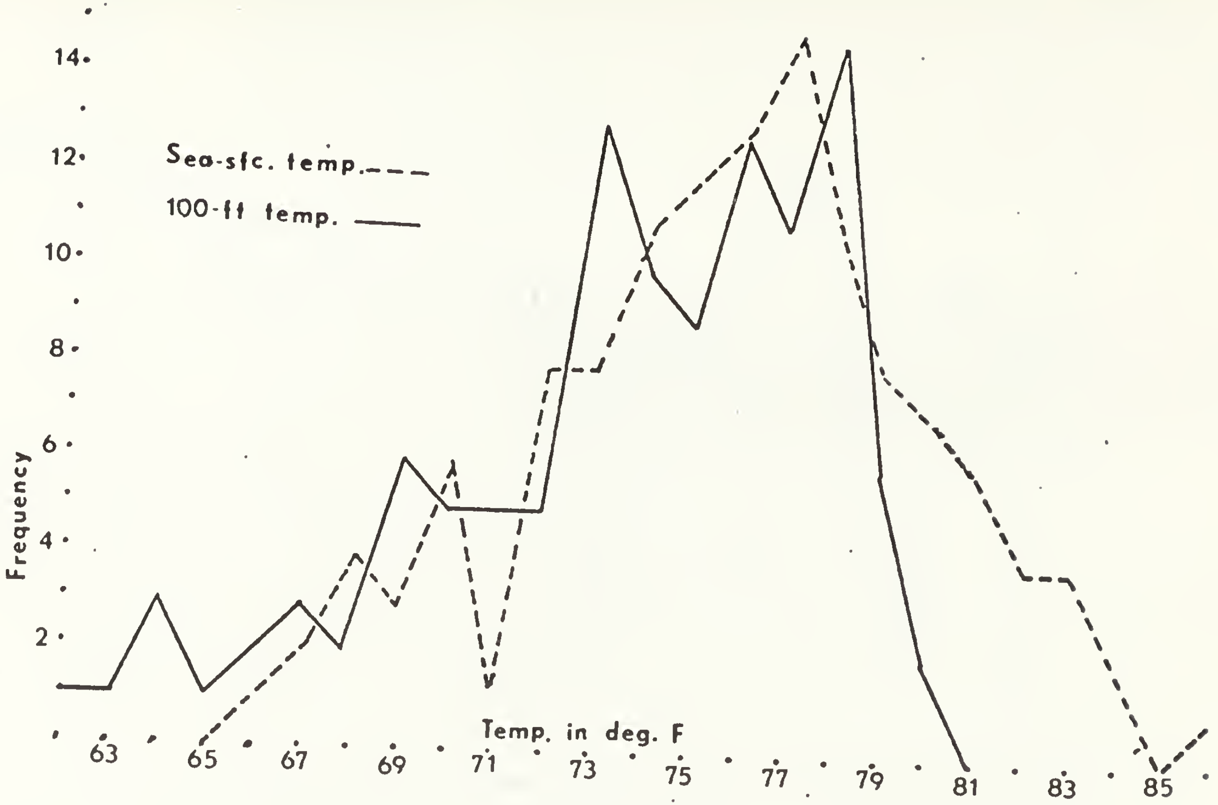


Figure 18. Dissipation frequency related to sea-surface and 100-foot ocean temperatures.

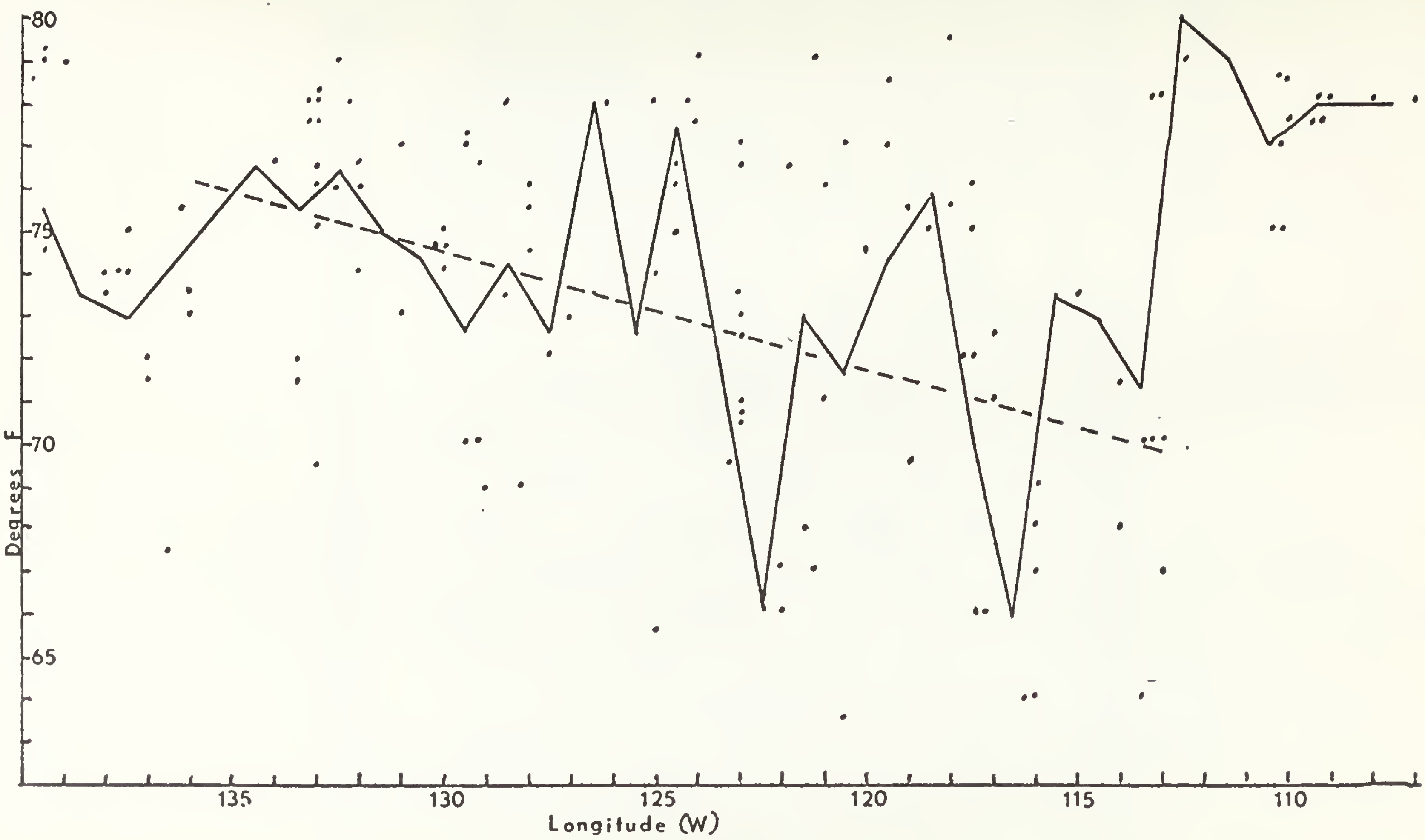


Figure 19. Variation of 100-foot water temperature with longitude at the points of dissipation of 120 EASTROPAC cyclones.

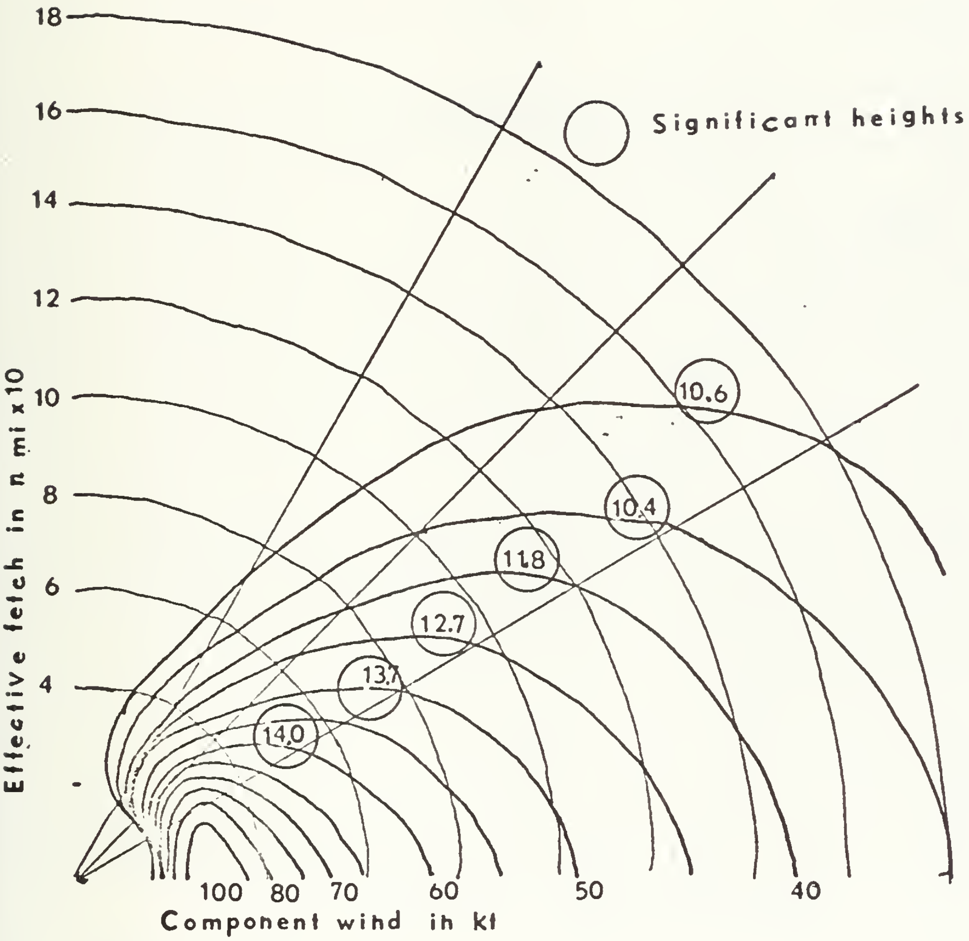


Figure 20. Significant wave heights in a circular stationary EASTROPAC model tropical cyclone.

Figure 21. Frequency of winter gales in the Gulf of Tehuantepec, 1962-1971.

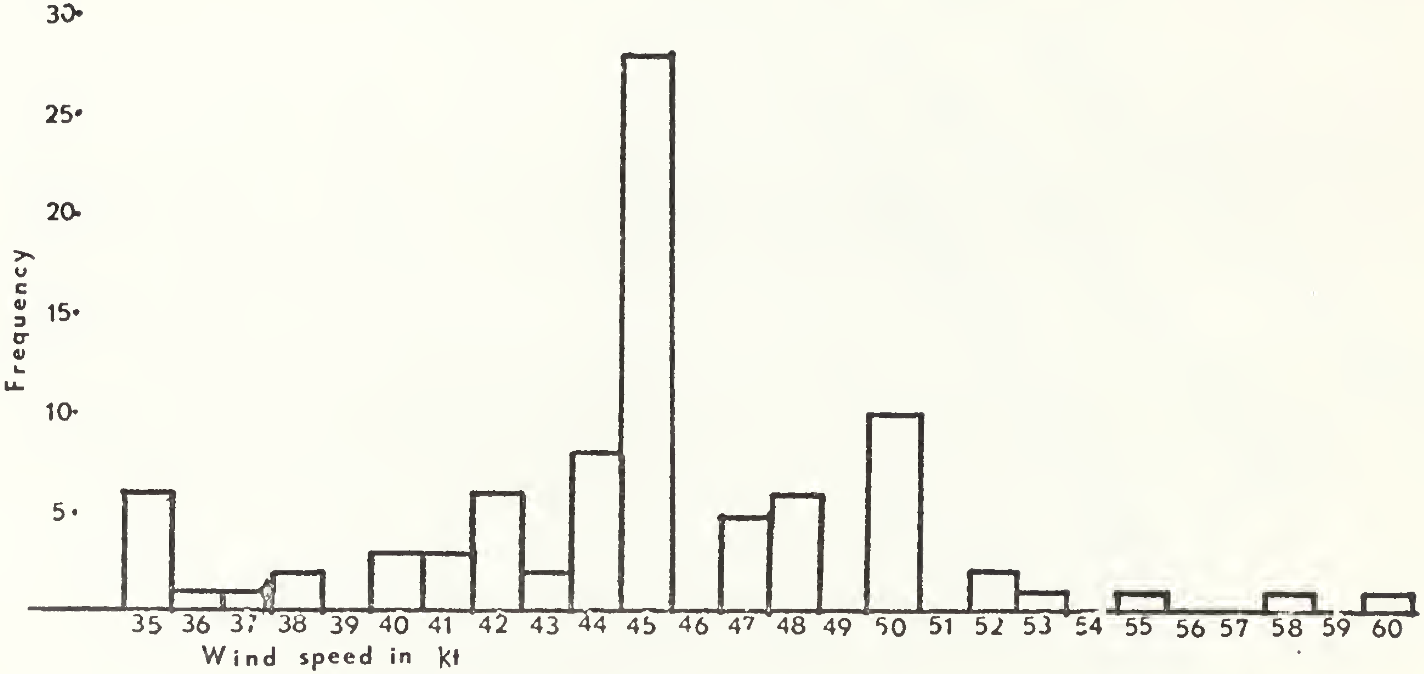


Figure 22. Frequency of reported wind speeds in winter gales in the Gulf of Tehuantepec, 1962-1971.

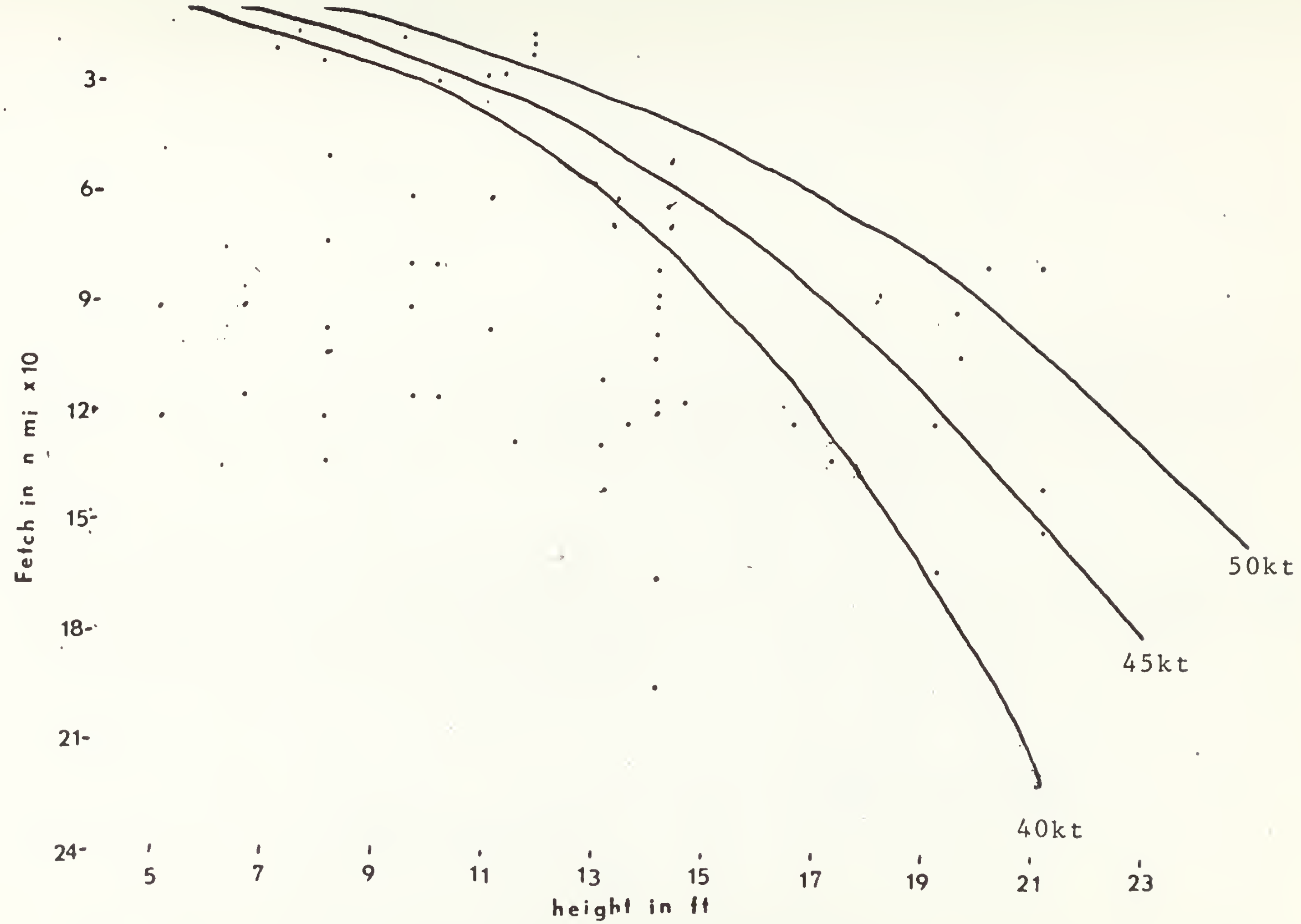


Figure 23. Theoretical and reported sea height (Ft) vs fetch (n mi). (Sverdrup-Munk-Bretschneider curves show maximum sea states for limiting fetch for 40, 45 and 50 kt winds.)

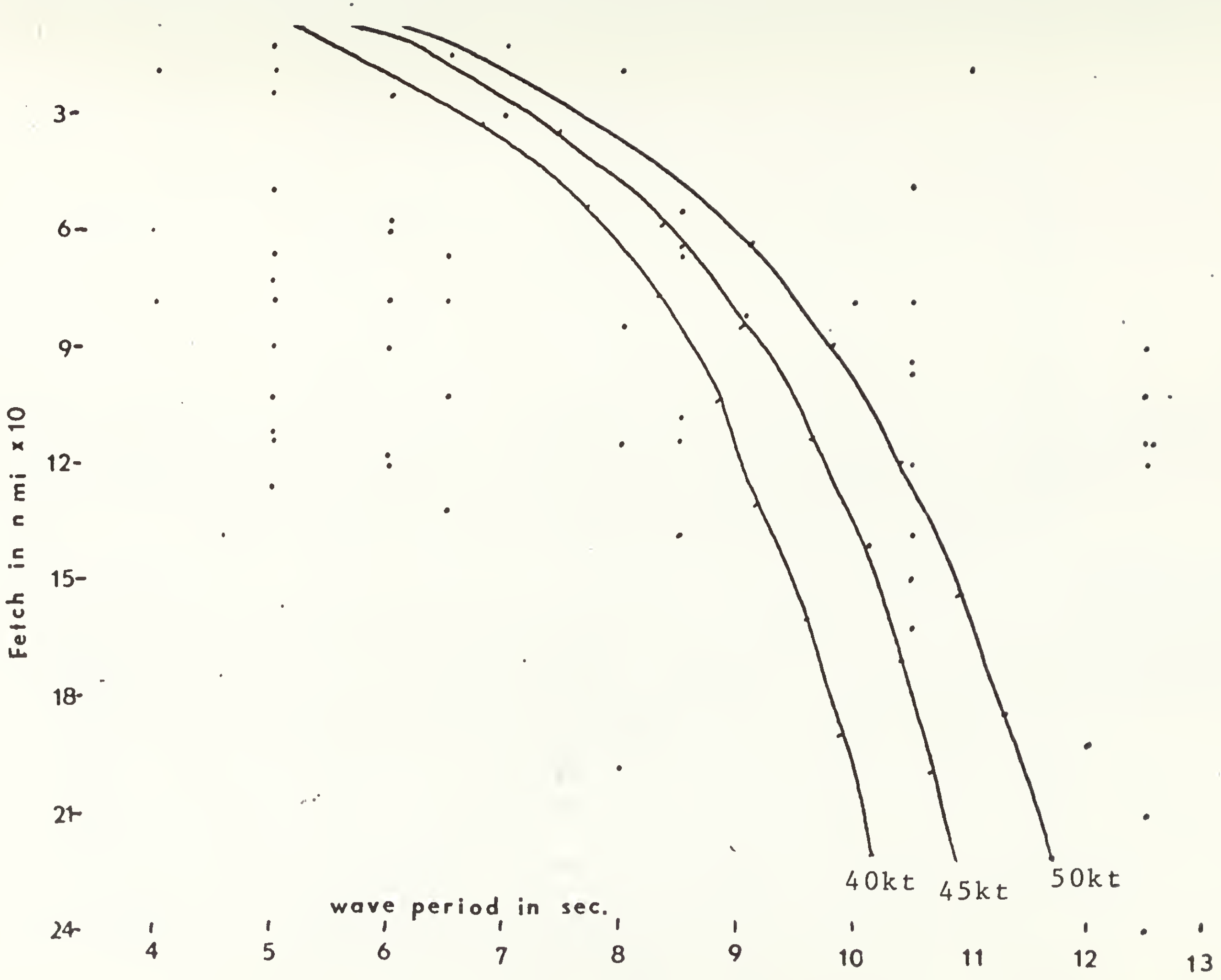


Figure 24. Theoretical and reported wave period vs fetch. (Sverdrup-Munk-Bretschneider curves for 40, 45 and 50 kt fetch-limited waves.)

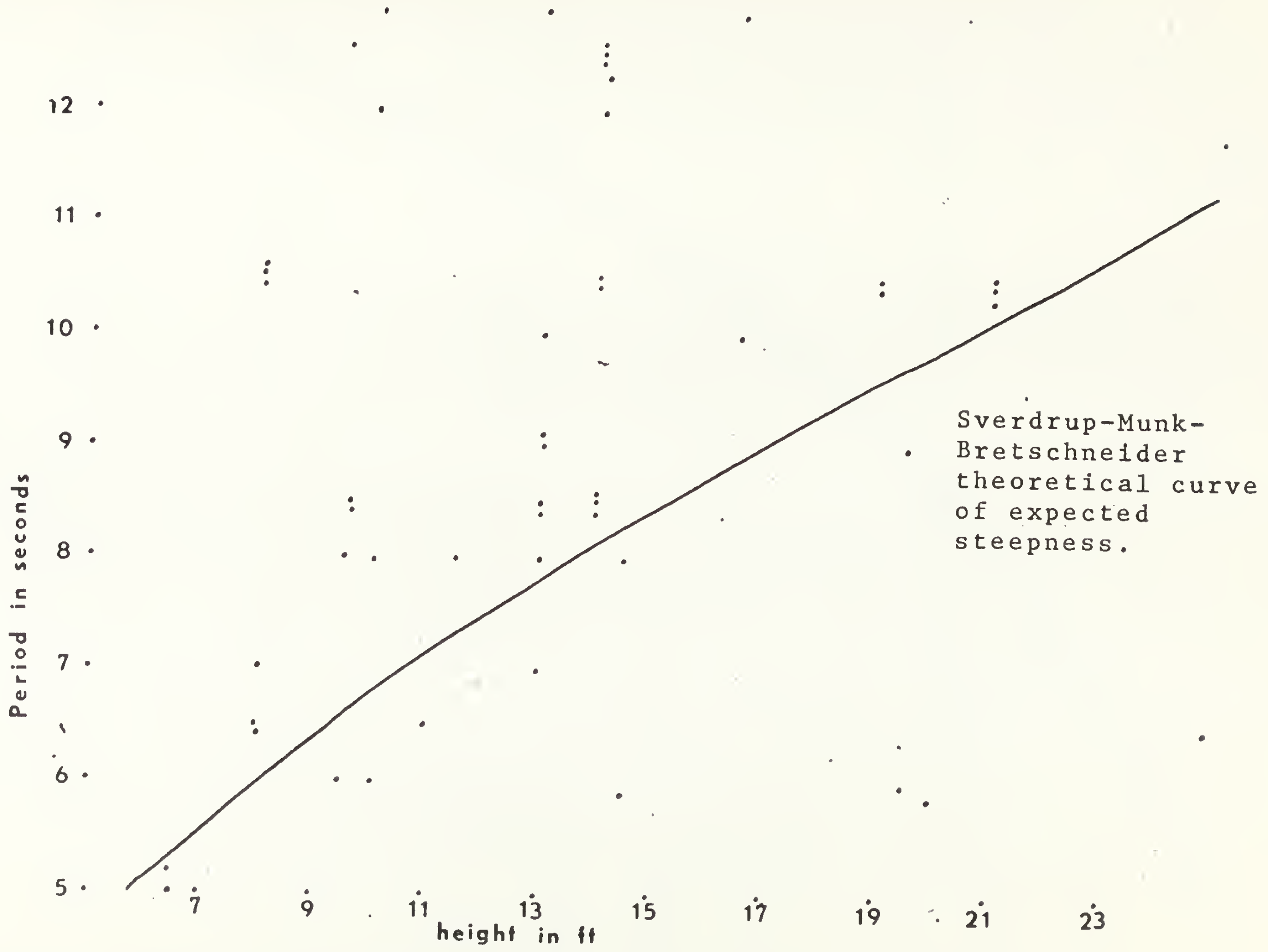


Figure 25. Theoretical and reported wave period vs wave height.

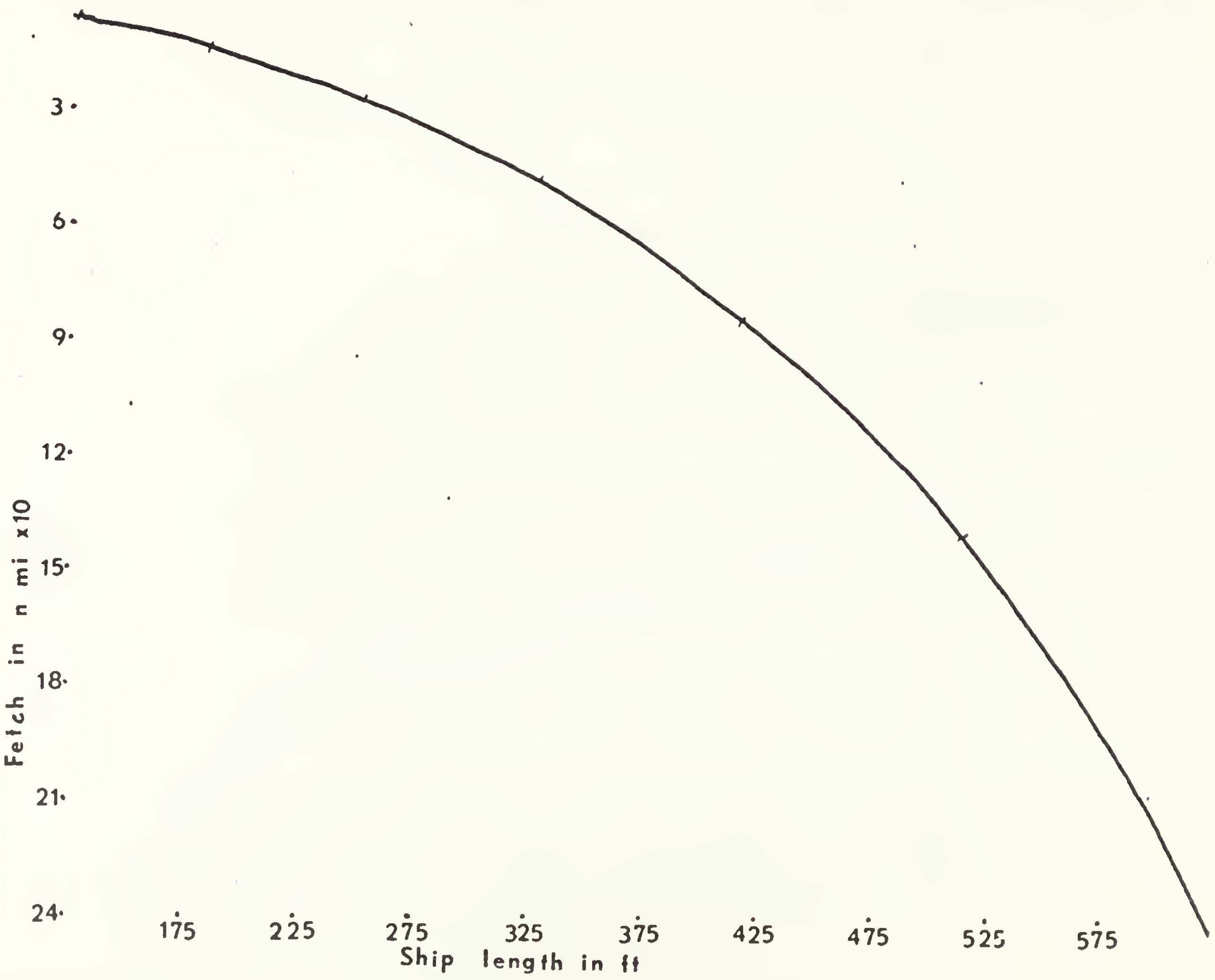


Figure 26. Fetch vs critical ship length (45 kt winds).

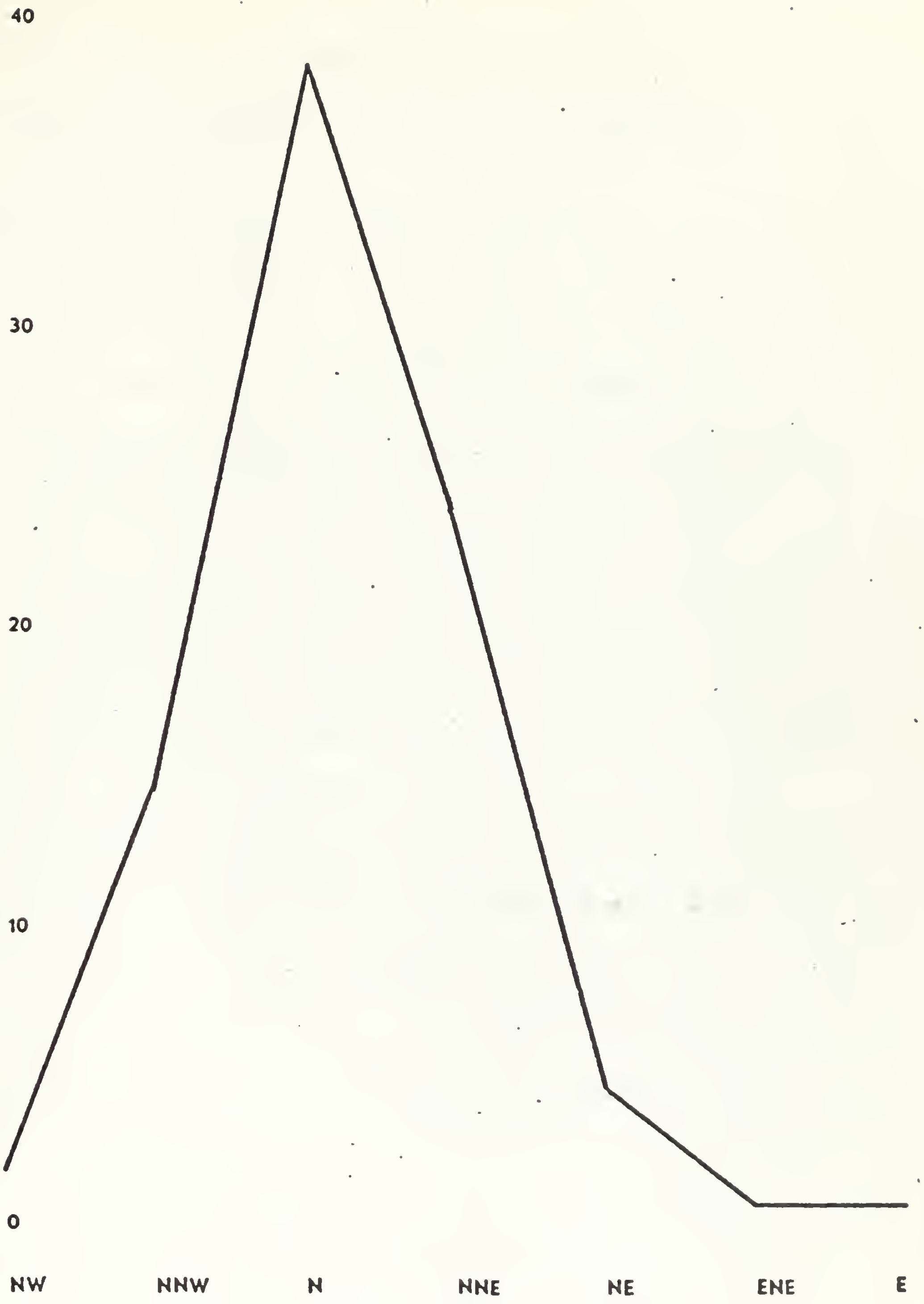


Figure 27. Frequency of reported wind direction in winter gales in the Gulf of Tehuantepec, 1962-1971.

APPENDIX A

GALE FORCE WINDS IN THE GULF OF TEHUANTEPEC

A study of ship weather reports from 1962 to 1971 in EASTROPAC revealed a winter peak frequency of gale-force northerly winds in the Gulf of Tehuantepec. These winds, termed Tehuantepecers by Hurd (1929), are associated with clear or clearing conditions in contrast to the increasing clouds and rain found near tropical cyclones. Seasons for the two types of disturbances are depicted in Figure 21 and overlap from mid-May to mid-June and again in the month of October. An understanding of these winter-season gales is therefore necessary to properly analyze and forecast conditions relative to the probable indicators of tropical-cyclone formation in the Gulf of Tehuantepec.

The source region for the air mass of the winter gale is west central Canada. Cold outbreaks of unusual severity or persistence move southward out of the Great Plains and along the east slope of the Sierra Madre Cordilla until reaching Chivela Pass (elevation 683 ft) and the Valley of Tehuantepec where it pours downslope into the Gulf of Tehuantepec of the Pacific causing nearly instantaneous increase of winds to 45 kt. Figure 22 shows a narrow range of reported wind velocities centered on 45 kt. Dynamically this is to be expected since katabatic winds descending from a fixed elevation into a tropical atmosphere of relatively uniform density should have similar terminal velocities. Lacking the signs

of increasing cloudiness, rain, falling barometer and gradually increasing sea and swell of tropical summer cyclones the winter gale presents a sudden and serious hazard. Sailing craft and fishing boats are particularly vulnerable to this storm.

Figures 23 and 24 show the theoretical 40 to 50-kt curves for sea height and period, respectively, according to the 1971 Bretschneider revision of the Sverdrup-Munk-Bretschneider (SMB) sea-development graph. Considering separately the accuracy of reported wave height and wind velocity the following conclusions are offered:

(1) Only a few reports deviate greatly from theoretical values and might be subject to transmission or serious observational errors.

(2) Conditions most often encountered are less severe than suggested by theory for that distance offshore. This is interpreted to indicate that winds at the time of reporting have been blowing for less than the minimum required time to develop the maximum sea that would be found if the winds continue.

(3) The usual reported wave height of 14 ft in a winter storm is reached in only 4 to 6 hr. A ship encountering a winter gale after it has been blowing for a short time finds a sharp increase from light winds to 45 kt beam winds and from slight seas to 14-ft and, on occasion, as much as 21-ft beam waves. By remaining close to shore a ship may avoid the highest waves. Figure 23 shows good agreement on a

limit of 11-ft waves 30 n mi offshore and 9-ft waves 20 n mi offshore. The low incidence (2 of 13 cases at 120 n mi) of fully developed seas further offshore suggests a short effective duration (usually less than 10 hr). Possibly by the time the air mass has travelled 120 n mi offshore there is seldom enough colder air remaining to sustain winds for ten additional hours.

Sparse data coverage in the Gulf of Tehuantepec makes it difficult to establish an accurate time profile of wind duration. Wind records from Salina Cruz 16.2N 95.2W and Ixtepec Military Airfield 16.5N 95.1W should be used for further study of the time variation of the surge, duration and recurrence of these winds. Hurd (op. cit.) reports durations of up to four days with intermittent gale-force winds. In January 1928, a record monthly total of eleven days was recorded.

Arnerich (1971) mentioned that the seas are said to be peculiarly short. Figure 25 is a measure of wave length to test this observation. Only eight cases of 54 (15 percent) were significantly shorter for their height than the SMB theoretical curve. The sample waves are not usually shorter than theory would predict for fetch-limited wind areas. It is observed from Figures 23 and 24 that both wave period and wave height increase with increasing fetch length while Figure 25 indicates a nearly linear increase of height with increasing period (slope - .72). The steepness of waves (defined as wave height divided by wave length) is given in

Pierson, Neumann and James (op. cit.) by wave height/5.12 $(\text{period})^2$. Waves of shorter period are, by this relationship and Figure 25, exponentially steeper for shorter periods. A wave of six-second period and eight-foot height found about ten miles offshore has a steepness value of .056 while a ten-second wave 20.5 feet high has a steepness of .040. Theory in this example explains a natural increase in steepness of 40 percent between fetch limited ten-second waves and fetch-limited six-second waves close to shore.

A C-2 class freighter has a length of about 540 ft at the water line and will generally have to reduce speed encountering head seas of the same length as the ship. By avoiding head seas of the critical period (10.3 seconds) a better speed can be maintained. In the Gulf of Tehuantepec the problem is one of beam sea period vs the natural roll period of the ship, which is not as easy to generalize as the head sea problem. Figure 26 shows the distance offshore that a wave length equal to the ship length will first occur for a mean wind of 45 kt.

Distribution of wind reports throughout the storm area, outlined in Figures 22 and 27, seems to indicate a relatively uniform wind condition throughout the Gulf of Tehuantepec during winter storms. Anticyclonic turning of Tehuantepecer winds is noted in Figure 2. Parmenter (1970) has documented the spread of cold air from satellite photographs of a squall line that moved offshore on 3 February 1970. No supporting gale-force ship reports have been found for this outbreak.

The pictorial evidence shows the leading edge of the cooler air mass moving at 22.5 kt during the first ten to twelve hours as the squall line becomes less marked. It would seem that cold air-mass characteristics would be present behind the squall line. Cool, dry, more dense air might be anticipated in a winter gale than would be found in surrounding regions. More marked contrast should be present near shore before the air mass has been modified in traveling over a warm sea.

A sample of ten years of sea-air temperature differences from reported gale winds in the Gulf of Tehuantepec was separated into three categories: (Case 1) winter gales, (Case 2) tropical cyclones with no rain occurring at time of observations, and (Case 3) tropical cyclones with rain at time of observation. The algebraic mean for winter gales showed the sea warmer than air by 1.5F. Case 2 indicated that summer tropical cyclones have nearly the same difference (1.4F). Hurd (op. cit.) reported the observations of the British steamer Nictheroy during the passage of a winter gale on 27-29 January 1928. Characteristics included initial calm seas, a passing arch shaped cloud "the width of a rainbow" extending from horizon to horizon, a cloudless sky following with winds north-east by north, force 9, and seas very heavy. The ship hove to and reported a temperature fall from 73 to 68F. The wind moderated rapidly and the temperature increased after noon of the 29th. The ship was then in motion, however, and these changes may represent horizontal as well

as temporal changes. The evidence of a cooler air mass is unmistakable with sharp boundaries marked in this instance and in the report of Parmenter (1970) by a squall-line type arched cloud.

The sudden onset of winds over the Gulf of Tehuantepec will result in rapid build up of sea with the short periods developing most rapidly. Figure 24 shows a reported increase of period with decreasing latitude. The hypothetical conditions for the theoretical curves are an initially undisturbed sea and an instantaneous beginning of 45-kt winds, very close to the actual conditions in a winter gale.

Katabatic winds descending from Chivela Pass to sea level would be subjected to adiabatic heating of about 4.0F. In the current study, 24 cases of time and space difference in reports were computed. A decrease in temperature northward within the air mass of winter gales was noted in 18 cases, indicative of further air mass modification by warming from beneath. Discarding the two largest and two smallest gradients as most likely to contain observational error a mean gradient of .09F per mile is calculated.

Evidence for the presence of a cool dry air mass over the Gulf of Tehuantepec on 1 October 1970 is found in the 1800 GMT report of Philippine Corregidor at 14.7N 94.6W. Dust or sand was reported with wind from the north at 45 kt. This same air was swept into the periphery of developing hurricane Patricia about 36 hr later.

Gale force winds in the Gulf of Tehuantepec are associated with both tropical cyclones and cold Canadian outbreaks which follow the eastern slopes of the Sierra Madre Cordilla in Mexico and pour through Chivela Pass into the Pacific Ocean. The seasons of winter gales and tropical-cyclone gale winds overlap in spring and fall. The suddenness, intensity and lack of visible warning of the onset of the winter gales present a serious forecasting and warning problem that is not yet completely solved.

Interest in this area is continuing. The _Naval Research Reviews_ for June-July 1972 noted that the schedule of the Scripps Institution of Oceanography research vessel George Melville includes a study of wave growth rates in the Gulf of Tehuantepec in mid-January 1973, the middle of the normal season of "tehuantepecer" winds. Also, the NOAA Technical Memorandum NWS WR 68 of July 1971 stated the need for a Gulf of Tehuantepec extended forecast.

The following chronological list of known gale-force "tehuantepecer" winds is provided as a starting point to develop the above extended forecast.

Chronological Record of Known Gale Force Winds
July 62 - October 71

Date	Number of Ship Reports Available*	Date	Number of Ship Reports Available*
26 Oct 1962	1	13 Feb 1967	2
13 Dec 1962	2	16 May 1967	1
22 May 1963	1	23 May 1967	1
16 Oct 1963	1	18 Oct 1967 -	
29 Nov 1963 -		19 Oct 1967	3
01 Dec 1963	3	19 Nov 1967	1
24 Dec 1963 -		23 Dec 1967 -	
25 Dec 1963	2	24 Dec 1967	3
31 Dec 1963	1	07 Feb 1968	1
05 Jan 1964	1	23 Mar 1968	3
07 Oct 1964	1	26 Oct 1968	1
20 Oct 1964 -		21 Nov 1968	1
22 Oct 1964	4	09 Dec 1968	1
01 May 1965	1	21 May 1969 -	
23 Oct 1965 -		24 May 1969	3
25 Oct 1965	3	19 Nov 1969 -	
09 Jan 1966	1	20 Nov 1969	2
23 Jan 1966	1	25 Nov 1969	1
27 Jan 1966 -		13 Dec 1969	1
30 Jan 1966	4	26 Dec 1969	1
05 Feb 1966	1	07 Jan 1970 -	
23 Feb 1966 -		10 Jan 1970	4
24 Feb 1966	3	31 Jan 1970	1
05 Mar 1966 -		10 Feb 1970	2
06 Mar 1966	5	17 Feb 1970	2
07 Jun 1966 -		04 May 1970	3
08 Jun 1966	2	01 Oct 1970	1
26 Oct 1966	1	16 Nov 1970	1
03 Nov 1966 -		28 Jan 1971	1
04 Nov 1966	2	04 Mar 1971	2
28 Nov 1966 -		21 Mar 1971	1
29 Nov 1966	2	07 Apr 1971 -	
04 Jan 1967 -		08 Apr 1971	4
05 Jan 1967	2		

50 Cases   93 Reports

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*Source of data <u>Monthly Weather Review</u>, "Routh Weather Log' Feature, Jun 62 - Oct 71

APPENDIX B

EASTROPAC Recurving Storm Track Summary 1956-1971

Chronological List of Storms

YEAR	NAME	ORIGIN	RECURVE	DISSIPATED	COURSE		L/S
					Before	After	
1957		1 Oct 17.5N118.2W	2 Oct 19.0N121.0W	25.9N112.0W	299	040	L
1957		17 Oct 14.0N104.0W	19 Oct 18.2N107.0W	21.5N105.8W	331	012	L
1957		Uncertain	20 Oct 16.0N111.0W	23.0N106.0W		033	L
1958		5 Jun 12.0N97.7W	13 Jun 20.0N111.3W	23.5N108.6W	301	035	S
1958		Uncertain	29 Oct 18.5N106.0W	20.8N105.8W		011	L
1959		22 Oct 13.0N96.9W	26 Oct 18.0N106.0W	19.0N104.3W	300	060	L
1961	H. Tara	10 Nov 14.7N101.5W	10 Nov 15.5N104.7W	17.5N101.4W	286	058	L
1962	H. Doreen	1 Oct 14.0N104.3W	4 Oct 22.3N109.4W	25.1N108.2W	330	025	L
1963	TS Lillian	24 Sep 17.2N102.2W	27 Sep 20.5N108.0W	22.2N105.8W	302	049	L
1963	H. Mona	Uncertain	17 Oct 19.0N110.8W	24.4N107.8W		029	L
1965	TS Hazel	23 Sep 19.0N109.5W	24 Sep 20.0N110.0W	23.5N106.6W	333	040	L

YEAR	NAME	ORIGIN	RECURVE	DISSIPATED	COURSE		L/S
					Before	After	
1966	H. Adele	21 Jun 16.1N101.2W	23 Jun 16.8N104.0W	18.5N103.2W	281	024	L
1966	H. Francesca	5 Sep 15.0N106.0W	12 Sep 20.0N130.2W	21.5N125.0W	282	071	S
1966	H. Helga	9 Sep 14.5N104.0W	13 Sep 22.5N117.0W	26.5N113.0W	303	045	L
1966	TS Kirsten	25 Sep 18.0N114.5W	26 Sep 19.5N115.0W	26.3N109.3W	343	037	L
1967	H. Lily	5 Sep 12.0N105.0W	9 Sep 24.5N122.8W	30.0N122.0W	306	042	S
1967	TS Monica	13 Sep 17.0N107.0W	18 Sep 17.5N113.3W	18.5N111.5W	275	060	S
1967	TS Nanette	13 Sep 15.0N111.0W	19 Sep 20.5N130.0W	21.0N124.0W	287	085	S
1967	H. Olivia	5 Oct 13.0N108.0W	10 Oct 15.5N114.7W	24.0N111.1W	292	022	L
1968	H. Naomi	8 Sep 12.5N98.5W	11 Sep 20.5N107.0W	24.5N106.3W	314	058	L
1968	H. Pauline	28 Sep 14.5N101.5W	1 Oct 23.0N111.5W	26.5N110.0W	311	028	L
1969	TS Irah	30 Sep 16.0N112.0W	1 Oct 17.0N115.8W	17.5N114.5W	285	064	S
1969	H. Jennifer	8 Oct 14.0N102.5W	10 Oct 19.5N108.5W	24.5N106.8W	313	022	L
1970	TS Norma	31 Aug 16.0N102.0W	4 Sep 23.8N115.0W	26.8N113.2W	302	029	L

YEAR	NAME	ORIGIN	RECURVE	DISSIPATED	COURSE Before	COURSE After	L/S
1970	TS Selma	1 Nov 14.5N108.5W	2 Nov 16.5N111.8W	22.3N112.6W	302	033	S
1971	H. Olivia	20 Sep 12.0N91.6W	29 Sep 23.0N114.7W	27.0N113.5W	298	019	L
1971	H. Priscilla	6 Oct 10.4N90.0W	11 Oct 19.5N106.3W	21.5N105.4W	300	022	L
1971	TS Ramona	28 Oct 10.9N101.1W	30 Oct 15.0N110.5W	16.1N108.9W	295	054	S
Means					302	040	
S.D.					17.1	17.4	

APPENDIX C

EASTROPAC Hurricane Track Data 1965-1971

NAME	DATE	CENTRAL POINT	STRENGTH	SPEED kt	PERIOD/	DIR. (DEG)
Emile	8/30/65	18.0N109.0W	55-60kt	10.0	24 hr.	340
	8/31/65	20.4N109.7W	60	12.0	6	340
	8/31/65	23.0N111.0W	60-80	10.6	30	330
	9/2/65	25.3N114.0W	80-45	3.7	42	270
	9/3/65	27.0N116.1W	45-30	9.0	30	350
Adele	Track entirely within 120NM of 17N 103W, erratic in nature, a form of recurver. Mean speed 6 kt.					
Blanca	8/3/66	16.9N117.5W	50.	15.0	18	280
	8/4/66	17.9N122.5W	50	18.0	18	315
	8/5/66	21.0N127.5W	50-65-50	13.0	18	285
	8/6/66	21.0N132.5W	50-60-30	14.5	24	270
Connie	8/8/66	14.0N123.0W	unk.	9.2	18	270
	8/10/66	14.0N127.5W	unk.	7.5	36	270
	8/10/66	14.3N131.6W	unk.	11.0	18	285
	8/11/66	15.2N134.5W	unk.	15.0	6	275
	8/11/66	16.2N137.5W	unk.	12.0	24	290
	8/13/66	17.9N142.5W	55-75	7.5	42	280
	8/15/66	17.4N147.5W	75-45	7.9	36	260
	8/16/66	17.1N152.5W	45-40	10	30	270
	8/17/66	17.1N156.5W	40-25	10	18	270
Dolores	8/17/66	14.5N103.7W	60	11	12	290
	8/17/66	15.8N105.8W	60	16	6	300
	8/17/66	15.6N107.0W	60	15	6	240
	8/18/66	14.1N108.5W	60-65	15	12	240
	8/18/66	14.0N111.2W	65-70	15	12	300
	8/19/66	16.0N113.7W	75-70	16	12	310
	8/19/66	18.0N116.7W	65-60	17	18	320
	8/20/66	21.4N118.5W	60-55	16	12	320
	8/20/66	21.9N122.5W	55-50	18	18	265
	8/21/66	23.1N127.5W	45-35	10.7	30	290
	8/22/66	24.3N131.0W	35	9	18	290
	8/23/66	25.6N134.0W	35-30	11	12	285
	8/24/66	26.1N137.5W	30-20	4	60	285
Eileen	8/23/66	17.7N113.0W	25-50	8.5	24	290
	8/24/66	19.0N117.5W	50-55	9.1	36	285
	8/25/66	19.6N120.9W	55-60	10.5	12	285
	8/26/66	20.5N124.0W	60-70	9.5	18	285
	8/27/66	20.9N126.5W	70-60	9.0	24	285
	8/28/66	23.2N129.0W	60-35	7.0	30	350

NAME	DATE	CENTRAL POINT	STRENGTH	SPEED kt	PERIOD/	DIR. (DEG)
Francesca	9/6/66	15.7N108.0W	25-40	15.0	18	290
	9/7/66	17.1N112.5W	40-65	10.0	30	285
	9/8/66	17.6N117.5W	65-60	11.8	24	270
	9/9/66	17.2N122.5W	55-50	13.0	24	260
	9/10/66	16.3N126.8W	50	12.0	18	260
	9/10/66-9/13/66*					
	9/13/66	18.0N129.4W	50	10.0	24	350
	9/15/66	21.0N128.0W	50-25	5.9	48	060
Helga	9/9/66	14.8N106.5W	30-45	10.5	18	270
	9/10/66	15.7N109.5W	50-55	10.0	12	290
	9/11/66	16.4N112.5W	55-65	11.5	30	290
	9/12/66	19.0N115.8W	65-75	11.0	18	340
	9/13/66	22.5N116.1W	75-60	10.0	36	360
	9/14/66	25.5N115.5W	60-50	8.0	12	050
	9/15/66	26.4N114.5W	50	7.5	12	050
Carlotta	6/22/67	13.5N102.0W	30	9.5	18	350
	6/23/67	12.6N103.8W	40-55	9.2	24	310
	6/24/67	18.4N107.1W	55-65	11.3	30	295
	6/26/67	21.5N113.1W	65-35	9.7	30	310
Jewell	7/17/67	16.4N114.0W	45-55	10.0	12	275
	7/18/67	17.8N117.5W	55-70-55	10.0	30	285
	7/19/67	19.5N120.5W	55-45	11.0	6	310
	7/20/67	21.6N123.4W	45	12.0	30	310
	7/21/67	23.8N126.6W	45-30	6.7	24	310
Katrina***	8/29/67	18.6N108.6W	45-55	10.0	6	270
	8/30/67	19.4N110.2W	55	12.0	12	345
	8/31/67	22.5N111.2W	55-70-60	11.0	24	345
	9/1/67	27.5N112.3W	60-40	12.0	24	345
Lily	9/5/67	13.3N108.0W	40-50	10.0	48	270
	9/6/67	13.2N112.5W	50-70	10.0	24	290
	9/7/67	16.7N118.0W	65-75	12.5	24	310
	9/8/67	19.4N121.0W	70	13.5	12	310
	9/9/67	21.5N122.2W	80	10.0	24	345
	9/9/67	24.2N123.0W	65	8.0	6	025
	9/10/67	26.3N121.3W	65-60	10.0	24	040
	9/11/67-9/12/67*					
Priscilla	10/14/67	13.6N103.2W	50-60	9.5	24	310
	10/16/67	16.2N107.5W	60-70	8.3	42	300
	10/17/67	19.0N111.4W	70-80	9.0	18	305
	10/19/67	19.6N117.5W	60-50	11.0	24	260
	10/20/67	18.9N122.5W	40-40	11.0	18	260
	10/20/67	18.0N127.0W	40-30	12	24	250

NAME	DATE	CENTRAL POINT	STRENGTH	SPEED kt	PERIOD/	DIR. (DEG)
Fernanda	8/5/68	12.5N107.5W	TD	8.0	30	270
	8/5/68	13.9N112.5W	TD-TS	11.0	30	295
	8/7/68	14.8N116.1W	-TS	11.0	18	280
	8/8/68	15.3N119.0W		11.0	12	280
	8/9/68	15.3N122.5W		11.6	24	270
	8/10/68	15.8N127.5W		12.4	24	275
	8/11/68	17.2N132.5W		11.8	30	300
	8/12/68	19.4N136.0W		10.4	24	285
	8/13/68	20.3N139.5W		5.0	12	285
	8/14/68	21.3N141.6W	TS	6.6	36	310
Joanne	8/21/68	11.0N109.0W	TD	6.5	12	280
	8/23/68	12.0N112.5W	TD	10.6	24	280
	8/24/68	13.0N116.3W	TD-TS	9.0	24	320
	8/25/68	16.7N118.2W	-TS	9.4	30	320
	8/26/68	18.5N112.0W	-TS	14.0	12	305
	8/26/68	21.0N124.1W	-TS	17.5	12	325
	8/27/68	24.0N126.5W	-TS	18.0	12	310
	8/27/68	24.0N131.5W	TS-TD	18.0	12	250
Lisa	9/28/68	13.0N104.0W	TS	12.0	12	290
	9/29/68	14.0N107.5W	TS	14.0	18	280
	9/30/68	14.4N111.1W	TS	13.5	18	290
	9/30/68	15.7N114.0W	TS	14.0	12	300
	10/1/68	16.8N117.5W	TS	12.5	24	285
	10/2/68	18.9N121.0W	TS	8.0	24	320
	10/3/68	22.1N123.5W	TS	7.5	48	320
	10/6/68	24.0N127.0W	TS	5.0	48	260
Naomi	9/8/68	12.4N99.4W	TD	10	6	270
	9/9/68	13.5N102.5W	TD	10.3	30	295
	9/11/68	17.5N107.2W	TD-TS	8.3	42	335
	9/12/68	22.0N107.5W	?	10.5	24	010
Pauline	9/28/68	14.5N102.1W	TS	3.3	24	290
	9/30/68	15.9N103.9W	-TS	4.6	30	300
	10/1/68	18.0N107.4W	-TS	12.0	24	310
	10/1/68	20.9N109.2W	-TS	14.0	12	320
	10/2/68	22.2N111.1W	-TS	13.0	12	310
	10/2/68	24.3N111.6W	-TS	13.0	12	030
Rebecca	10/5/68	13.8N98.7W	TD	4.5	48	300
	10/8/68	16.7N102.6W	TS	8.0	48	300
	10/9/68	18.5N107.5W	TS	9.6	30	280
	10/10/68	19.3N111.0W	TS	11.5	12	310
	10/11/68	21.2N112.7W	TS-TD	5.7	42	320
Bernice	7/9/69	12.7N103.0W		8.5	36	260
	7/10/69	11.5N106.5W		12	12	250
	7/11/69	12.7N108.9W		5.0	36	320
	7/12/69	14.0N111.9W		9.5	24	295

NAME	DATE	CENTRAL POINT	STRENGTH	SPEED kt	PERIOD/	DIR. (DEG)
	7/13/69	15.3N114.5W		10	6	290
	7/14/69	16.5N117.5W		10.8	30	290
	7/15/69	18.3N122.5W		13.0	24	290
	7/16/69	19.3N127.5W		12.0	24	270
	7/17/69	19.3N131.1W		9.0	12	270
Doreen	8/5/69	17.8N108.8W		6.0	24	300
	8/6/69	19.0N111.1W		11.0	18	300
	8/6/69	20.6N114.0W		9.0	12	300
	8/8/69	21.5N117.5W		7.9	48	280
Glenda	9/8/69	16.0N102.5W		12.0	24	295
	9/9/69	18.8N106.3W		12.0	18	330
	9/10/69	20.7N109.0W		11.0	12	300
	9/11/69	23.3N112.5W		12.0	30	310
	9/12/69	25.7N116.2W		8.6	18	290
Jennifer	10/8/69	14.7N103.4W		15.0	6	300
	10/9/69	15.4N104.5W		15.0	6	300
	10/9/69	16.3N106.0W		15.0	12	300
	10/10/69	18.5N106.9W		5.8	30	360
	10/11/69	22.0N107.0W		6.0	42	360
Francesca	7/2/70	10.8N92.8W	?	10	24	270
	7/3/70	11.0N97.5W	-40	14	18	280
	7/4/70	12.0N102.5W	40-50	13	18	280
	7/5/70	13.0N107.5W	50	15	18	290
	7/6/70	14.0N112.5W	50-40	12.5	24	290
	7/7/70	15.9N118.0W	40-30	8.5	36	280
Lorraine	8/17/70	15.6N108.5W	30-35	13	18	280
	8/18/70	15.5N110.7W	35-50	9	12	250
	8/19/70	14.6N113.7W	50-60	10	18	250
	8/20/70	14.2N117.2W	65	9.3	30	280
	8/21/70	16.5N122.5W	65	12	30	290
	8/23/70	17.0N127.5W	65-60	11	30	275
	8/24/70	18.0N132.5W	60-45	10.1	30	290
	8/26/70	19.8N137.5W	45-30	9.7	36	290
Pat	10/5/70	12.8N102.5W	?	11.0	24	275
	10/6/70	13.7N107.5W	?	12.0	24	285
	10/6/70	14.5N110.6W	90	15.0	6	280
	10/7/70	15.4N113.4W	90	15.0	12	280
	10/8/70	16.0N117.5W	90-95	12.0	24	275
	10/9/70	16.6N122.5W	95	10	30	280
	10/10/70	18.3N127.5W	95-40	8.3	36	290
	10/11/70	19.0N131.0W	40-30	7.0	12	270
Agatha	5/22/71	14.3N99.3W	50	9.5	6	310
	5/23/71	15.4N101.0W	50-60	9.5	18	310

NAME	DATE	CENTRAL POINT	STRENGTH	SPEED kt	PERIOD/	DIR. (DEG)
	5/24/71	16.8N102.0W	60-35	6.5	24	335
Bridget	6/15/71	12.0N93.0W	35	10.5	24	290
	6/16/71	14.0N97.2W	45-75	11.5	24	300
	6/16/71	15.3N99.5W	85	16.0	6	310
	6/17/71	16.8N101.0W	75-land	16.0	18	310
Denise	7/4/71	14.0N109.0W	45	10.2	12	260
	7/5/71	13.4N111.0W	50-55	10.2	12	260
	7/6/71	13.0N113.5W	60	11.5	18	270
	7/6/71	13.0N116.0W	65	11.5	18	270
	7/7/71	12.9N118.5W	70-80	9.7	24	265
	7/8/71	12.0N122.5W	80	16.2	18	265
	7/9/71	12.1N127.5W	70-110	16.2	18	275
	7/9/71	13.1N134.3W	65	14.0	6	285
	7/10/71	14.2N136.2W	60-35	14.0	18	290
	7/11/71	15.2N139.0W	45	14.0	6	280
	7/11/71	16.4N142.5W	65	13.0	24	290
	7/12/71	17.9N147.5W	60-40	13.0	24	265
	7/13/71	17.0N151.0W	35	10.0	6	265
Francene	7/19/71	14.5N111.2W	40	12.0	12	290
	7/19/71	15.5N114.0W	100	10.5	12	290
	7/20/71	16.1N116.2W	100-60	10.5	18	290
	7/21/71	16.9N119.0W	60	9.1	18	265
	7/22/71	16.2N122.5W	40	12.3	24	265
	7/22/71	16.3N125.5W	45	12.3	6	270
	7/23/71	16.0N129.0W	45-35	90	25	250
	7/24/71	14.2N131.0W	30	6.0	24	260
Hilary	7/26/71	11.0N113.5W	25-60	5.8	42	285
	7/29/71	13.0N117.0W	80-70	5.2	60	295
	7/31/71	14.9N121.1W	65-70	6.2	24	265
	8/1/71	13.9N124.0W	65-70	8.4	24	290
	8/2/71	16.7N126.8W	70	12.5	18	315
	8/3/71	17.8N129.0W	65	10	12	270
	8/4/71	18.4N132.5W	60-40	10	30	295
	8/5/71	19.9N137.5W	35	7.2	30	270
Ilsa	8/1/71	14.0N103.0W	30-65	15.0	12	290
	8/2/71	15.8N108.0W	80-90	16.0	18	290
	8/2/71	17.0N111.0W	90	16.0	12	300
	8/3/71	18.0N112.0W	90-100-80	2.0	24	340
	8/4/71	19.3N112.5W	80-75	10	12	335
	8/4/71	21.0N114.0W	65-50	9.2	12	290
	8/5/71	21.3N116.1W	50	8.4	18	290
	8/6/71	22.2N118.9W	50	13.5	18	290
	8/7/71	23.0N122.5W	50-30	8.5	30	270
	8/7/71	22.3N125.7W	30-30	8.5	6	270

NAME	DATE	CENTRAL POINT	STRENGTH	SPEED kt	PERIOD/	DIR. (DEG)
Lily	8/29/71	13.3N98.2W	30	13.0	18	285
	8/29/71	14.3N101.2W	30-35	12.0	12	290
	8/30/71	16.0N104.0W	45	11.0	18	320
	8/31/71	19.0N105.3W	65-75-70	9.0	24	355
Monica	8/30/71	13.0N113.5W	40-50	5.7	42	310
	9/2/71	17.5N114.9W	65-100-65	5.1	54	360
	9/4/71	22.0N114.5W	65-25	4.8	48	005
Nanette	9/5/71	17.5N105.2W	30-55	9.6	24	345
	9/7/71	20.5N108.7W	76-65	13.4	18	290
	9/8/71	21.1N112.5W	60-45	11.5	24	270
	9/9/71	21.0N117.0W	45-25	9.0	24	270
Olivia	9/20/71	12.5N88.5W	50	5.0	30	275
	9/22/71	13.0N92.5W	50-70	12.0	30	275
	9/23/71	13.5N97.5W	70-80	10.0	24	280
	9/24/71	14.5N101.5W	80	14.0	18	285
	9/25/71	15.1N104.0W	80	10.0	6	285
	9/26/71	17.2N108.0W	95	10.0	36	310
	9/27/71	19.8N111.0W	100-85	5.4	18	275
	9/28/71	21.2N114.0W	80-40	8.5	30	330
	9/30/71	26.0N114.5W	35	10	12	025
Priscilla	10/7/71	11.3N92.5W	30-40	8.0	42	300
	10/9/71	13.2N97.5W	40-80	11.6	30	285
	10/9/71	14.5N100.5W	90	12.3	6	285
	10/10/71	16.0N103.3W	90-110	12.3	18	300
	10/11/71	18.7N106.0W	110-70	7.5	24	320
	10/12/71	21.5N106.3W	70-60	9	18	020

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*This portion of the track was erratic in motion.

APPENDIX D

Known EASTROPAC Storms in Seasonal Order (1921 - 1971)

*DATE	YR.	CLASS	NAME	MAX	ORIGIN	END	REMARKS
May 17	56	H		81	15.0N110.0W	15.7N121.9W	
May 21	71	H	Agatha	60r	11.9N93.3W	17.9N102.0W	Onshore(340)
May 29	56	H		63	15.2N104.5W	16.9N115.5W	
May 31	70	TS	Adele	65r	11.0N102.1W	14.8N131.1W	
Jun 3	65	TS	Victoria	25	11.0N106.9W	19.5N123.0W	
Jun 5	30				11.5N94.0W	24.4N111.5W	Onshore(320)
Jun 6	58	H		60	12.0N97.7W	23.5N108.6W	
Jun 7	67	TS	Agatha	50	14.0N117.0W	15.2N125.6W	
Jun 8	60	TS	Annette	45	13.5N95.0W	16.2N110.4W	
Jun 9	56	H		75	16.7N105.1W	19.6N109.0W	
Jun 9	61	H	Iva	95	13.7N100.0W	24.8N102.0W	Onshore(350)
Jun 9	70	TS	Blanca	50r	13.1N117.0W	17.8N120.1W	
Jun 10	59	TS		45	17.0N106.0W	23.2N106.0W	Onshore(360)
Jun 12	56	H		101	13.5N96.5W	17.6N101.5W	Onshore(300)
Jun 12	58	TS		50	13.0N91.7W	16.2N94.7W	Onshore(330)
Jun 14	65	TS	Virginia		12.6N109.8W	16.0N120.5W	
Jun 14	71	H	Bridget	75	11.1N88.8W	18.0N102.2W	Onshore(330)
Jun 15	67	TS	Bridget	35	16.3N101.3W	17.3N102.7W	
Jun 16	65	TS	Wallie	45	14.8N98.2W	17.1N100.4W	Onshore(320)
Jun 17	70	TS	Connie	45r	12.0N109.0W	17.9N117.3W	
Jun 18	49				18.0N112.5W	24.3N117.4W	
Jun 18	54				14.3N94.5W	18.2N103.6W	
Jun 19	70	TS	Dolores		10.0N104.0W	11.1N105.7W	
Jun 20	68	TS	Annette	40	18.0N103.8W	19.5N104.6W	
Jun 21	60	TS	Bonny	45	14.0N102.7W	20.8N110.6W	
Jun 21	66	H	Adele	64	16.1N101.2W	18.5N103.2W	
Jun 22	67	H	Carlotta	50	12.0N102.0W	22.8N116.0W	
Jun 24	62	H	Valerie	60	16.8N104.0W	23.0N106.3W	Onshore(360)
Jun 26	59	TS		50	16.5N104.1W	21.0N114.0W	

DATE	YR.	CLASS	NAME	MAX	ORIGIN	END	REMARKS
Jun 27	70	TS	Eileen	35	16.0N102.9W	23.8N106.6W	
Jun 28	63	H	Emily	75	15.5N100.0W	18.3N103.4W	Onshore(330)
Jun 28	65	TS	Ava	35	15.2N108.5W	17.4N125.0W	
Jun 29	65	TS	Bernice	55	10.5N97.4W	18.5N130.0W	
Jul 2	69	TS	Ava	55	13.4N93.4W	20.0N110.3W	
Jul 2	70	H	Francesca	50r	11.0N90.6W	15.6N119.8W	
Jul 2	71	H	Carlotta	60r	10.3N107.5W	20.0N137.5W	
Jul 2	71	H	Denise	110r	10.8N98.6W	15.4N140.0W	Crossed 140
Jul 4	68	TS	Bonny	50	13.9N104.0W	23.9N120.7W	
Jul 5	26				10.8N99.0W	19.2N109.3W	
Jul 5	64	TS	Natalie	40	16.2N104.0W	24.0N107.2W	Onshore(350)
Jul 7	62	TS	Willa	45	19.8N110.8W	21.0N123.0W	
Jul 7	71	TS	Eleanor	40	11.2N107.0W	13.0N132.8W	
Jul 8	56	H		86	17.0N106.7W	20.0N123.0W	
Jul 8	67	TS	Denise	25	15.0N112.0W	16.0N147.0W	
Jul 8	69	H	Bernice	40	13.0N101.0W	19.3N132.2W	
Jul 9	57	TS			14.0N109.0W	29.5N120.5W	
Jul 10	55				16.2N105.0W	15.0N124.3W	
Jul 10	61	TS	Joanne	45	15.8N112.4W	14.9N118.7W	
Jul 12	55				15.5N97.0W	26.3N112.8W	Onshore(360)
Jul 13	67	TS	Eleanor	40	17.0N121.0W	20.0N133.0W	
Jul 14	56			48	14.8N121.1W	17.3N127.5W	
Jul 14	61	TS	Kathleen	60	16.5N106.5W	15.8N112.5W	
Jul 14	61	TS	Lisa	45	14.4N98.0W	25.1N121.2W	
Jul 14	63	H	Florence	70	18.5N109.0W	20.0N128.0W	
Jul 14	70	TS	Gretchen	45r	15.0N108.0W	18.0N123.0W	
Jul 15	57	H		70	11.0N109.0W	15.3N133.0W	
Jul 15	64	H	Odessa	65	15.0N111.6W	20.7N132.0W	
Jul 15	68	TS	Celeste	25	15.7N103.3W	24.0N129.5W	
Jul 16	59	TS		55	11.8N121.5W	20.0N132.0W	
Jul 16	70	TS	Helga	35r	17.0N104.0W	23.3N111.5W	
Jul 17	67	H	Jewell	65	16.2N113.3W	23.7N129.3W	
Jul 17	71	H	Francene	100r	11.2N104.7W	22.2N132.1W	
Jul 18	58	H		45	17.8N127.3W	17.5N133.0W	Maybe only TS

DATE	YR.	CLASS	NAME	MAX	ORIGIN	END	REMARKS
Jul 19	60	H	Celeste	45	16.3N103.0W	21.4N117.3W	
Jul 19	61	TS	Madeline	45	14.2N107.0W	14.1N112.4W	
Jul 19	63	H	Glenda	75	14.1N115.3W	14.0N124.0W	
Jul 20	64	TS	Prudence	40	12.0N113.0W	20.0N130.0W	
Jul 20	71	TS	Georgette	50r	15.5N103.7W	15.0N132.2W	
Jul 21	41				11.4N112.6W	18.7N132.8W	
Jul 21	58	H		65r	19.0N124.3W	18.5N132.2W	
Jul 21	59	TS		50	16.0N119.0W	17.0N134.0W	Origin Uncertain
Jul 21	68	TS	Diana	40	11.5N103.0W	17.0N132.0W	
Jul 21	69	TS	Claudia		13.0N129.5W	18.0N136.2W	
Jul 22	59	TS		35	16.0N119.9W	17.8N132.7W	
Jul 22	70	TS	Kone	48	15.0N101.5W	21.5N113.0W	
Jul 23	67	TS	Francene	55	12.0N96.0W	26.0N118.0W	
Jul 23	68	TS	Estelle	20	11.0N100.0W	15.7N141.8W	
Jul 25	54				17.2N113.5W	16.0N133.0W	
Jul 26	58	TS		55	15.8N100.0W	25.0N116.0W	
Jul 26	67	TS	Georgette	35	15.0N127.0W	21.0N137.0W	
Jul 26	71	H	Hilary	85r	9.9N109.6W	19.7N140.0W	Crossed 140W
Jul 28	59	TS		45	12.2N98.2W	14.0N101.0W	
Jul 29	70	TS	Joyce	50r	17.5N106.0W	19.3N118.8W	
Jul 30	54				15.1N120.1W	18.6N132.2W	
Jul 30	71	H	Ilsa	65r	11.8N97.7W	22.1N127.8W	
Jul 31	58	TS		force 9	16.1N111.5W	18.8N117.5W	
Aug 2	66	H	Blanca	41	15.9N114.0W	30.7N164.9W	
Aug 3	61	TS	Naomi		17.2N115.0W	18.0N121.0W	
Aug 4	29				17.0N106.0W	31.5N114.0W	Onshore (340)
Aug 4	59	TS		40	25.7N130.8W	26.0N133.0W	
Aug 4	68	H	Fernanda	30	12.1N104.3W	20.1N139.5W	
Aug 4	69	H	Doreen	50	17.0N107.5W	21.7N120.8W	
Aug 5	68	TS	Gwen	30	11.0N96.0W	20.6N119.2W	
Aug 5	70	TS	Kristen	40	16.0N103.0W	24.0N115.0W	
Aug 6	57	H		90	18.1N126.0W	42.0N172.0W	
Aug 6	71	TS	Jewel	45	15.2N99.8W	20.8N117.1W	
Aug 7	65	TS	Claudia	40	20.5N110.0W	30.0N125.0W	

DATE	YR.	CLASS	NAME	MAX	ORIGIN	END	REMARKS
Aug 7	66	H	Connie	50	14.0N122.0W	17.2N150.0W	
Aug 8	57	H		75r	13.0N106.0W	29.0N120.0W	
Aug 8	71	TS	Katrina	65	14.0N96.0W	25.5N109.0W	Onshore(360)
Aug 10	28				14.0N99.0W	34.0N119.0W	Onshore(360)
Aug 11	21				13.0N96.0W	18.3N113.5W	
Aug 11	67	TS	Ilsa	45	13.0N106.3W	20.5N123.0W	
Aug 12	58	TS		60	17.0N121.1W	17.7N129.3W	
Aug 16	60	H	Diana	75	14.8N98.5W	23.1N109.4W	Onshore(340)
Aug 16	62	TS	Ava	45	15.9N114.4W	23.0N119.0W	
Aug 16	66	H	Dolores	55	14.0N102.0W	26.4N139.5W	
Aug 16	68	TS	Hyacinth	42	17.0N108.0W	24.3N111.4W	Onshore(030)
Aug 17	67	H	Jewell	65	15.0N111.0W	24.0N126.0W	
Aug 17	70	H	Lorraine	65r	14.3N105.5W	20.0N140.0W	To Pearl
Aug 19	27				14.0N96.5W	18.2N103.1W	Onshore(360)
Aug 19	59	TS		25	19.0N111.0W	19.9N109.0W	Weak
Aug 20	62	TS	Unnamed		19.0N133.0W		Not tracked
Aug 20	64	TS	Roslyn	40	19.7N115.0W	21.8N122.0W	
Aug 20	65	TS	Doreen	60	13.4N109.0W	28.1N139.7W	
Aug 20	70	TS	Maggie	50r	13.0N130.5W	14.8N138.6W	
Aug 21	68	H	Joanne	68	11.0N108.0W	26.0N137.0W	
Aug 21	68	TS	Iva	45	13.5N98.5W	26.1N128.4W	
Aug 22	56			62	15.9N114.0W	20.5N131.5W	
Aug 22	69	TS	Emily	55	19.0N106.5W	24.0N116.0W	
Aug 23	64	TS	Sylvia	40	21.7N107.1W	23.5N111.0W	Very small
Aug 23	66	H	Eileen	70	16.7N111.7W	23.9N129.1W	
Aug 25	68	TS	Kathleen	40	14.2N110.2W	17.0N146.7W	
Aug 26	59	TS		55	18.0N129.9W	17.0N133.0W	
Aug 28	60	H	Estelle	95	11.5N91.0W	27.0N121.5W	
Aug 28	68	H	Lisa	75	12.5N103.5W	23.5N129.0W	
Aug 28	68	TS	Madeline	45	8.0N90.5W	10.8N96.4W	
Aug 28	71	H	Lily	80	13.0N93.3W	19.1N104.5W	Onshore(350)
Aug 28	71	H	Monica	75r	12.0N107.5W	23.0N114.9W	
Aug 29	65	H	Emily	80	16.0N108.0W	28.6N116.6W	
Aug 29	67	H	Katrina	85	17.0N106.0W	31.0N113.6W	Crossed Baha at 24N

DATE	YR.	CLASS	NAME	MAX	ORIGIN	END	REMARKS
Sep 1	28				13.0N108.6W	20.7N123.0W	
Sep 1	54				16.5N115.6W	16.7N133.0W	
Sep 1	62	TS	Bernice	60r	19.2N107.5W	25.8N113.0W	
Sep 1	70	TS	Norma	50r	18.0N107.5W	26.2N113.8W	
Sep 2	60	H	Fernanda	65	11.5N91.0W	19.0N110.0W	
Sep 2	69	TS	Florence	60	18.5N110.2W	24.2N113.3W	
Sep 2	71	H	Nanette	85r	11.9N95.0W	20.9N118.2W	
Sep 3	56	TS		40	15.6N115.1W	16.7N126.3W	
Sep 3	59	H	Fernanda	65	12.7N94.0W	19.0N110.0W	
Sep 4	38				11.0N92.5W	25.0N111.0W	Onshore(330)
Sep 4	67	H	Lily	85	12.8N106.0W	29.5N122.0W	
Sep 5	66	H	Francesca	45	15.0N106.0W	17.6N129.7W	
Sep 6	24				10.0N102.0W	18.0N102.4W	Onshore(020)
Sep 6	58	H		130	17.8N112.0W	17.1N129.6W	
Sep 6	61	TS	Orla	52	17.0N111.0W	27.7N116.0W	
Sep 7	64	TS	Tillie	35	20.3N109.3W	23.9N114.2W	
Sep 7	70	TS	Orlene	45	14.3N95.5W	14.3N99.0W	
Sep 8	65	TS	Florence	30	16.3N113.5W	19.2N130.0W	
Sep 8	66	TS	Gretchen	35	17.0N128.0W	16.0N139.5W	
Sep 8	67	H	Sarah	130	11.3N149.2W	18.0N180.0W	Westbound
Sep 8	68	H	Naomi	81	12.5N98.5W	24.5N106.1W	Onshore(040)
Sep 8	69	H	Glenda	40	14.8N100.0W	26.0N117.5W	
Sep 9	36				18.3N103.0W	23.1N109.6W	Onshore(350)
Sep 9	49				17.1N105.0W	23.1N110.2W	Onshore(010)
Sep 9	66	H	Helga	40	15.5N104.8W	26.6N114.1W	
Sep 10	31				17.4N104.4W	27.7N112.2W	
Sep 10	58	TS		40	20.1N107.1W	23.1N104.6W	Onshore(330)
Sep 11	66	TS	Ione	25	11.0N96.0W	16.5N102.5W	
Sep 12	56			61	17.0N106.5W	24.0N123.0W	
Sep 12	63	TS	Irah	45	18.7N124.8W	21.3N138.2W	
Sep 12	63	TS	Jennifer	45	16.5N111.0W	18.0N123.0W	
Sep 13	65	TS	Glenda	45	12.0N109.2W	22.6N133.4W	
Sep 13	67	TS	Monica	50	16.6N107.2W	17.9N112.1W	
Sep 13	67	TS	Nanette	34	15.0N111.0W	18.9N127.9W	

DATE	YR.	CLASS	NAME	MAX	ORIGIN	END	REMARKS
Sep 14	66	TS	Joyce	25	14.0N108.0W	15.2N118.1W	
Sep 15	34				10.3N91.9W	33.8N118.1W	
Sep 15	55				19.0N107.3W	20.3N127.0W	
Sep 17	41				10.8N99.2W	24.8N110.2W	
Sep 17	57	H		113	14.9N99.1W	17.4N101.1W	Onshore(340)
Sep 18	69	TS	Heather		13.5N122.5W	21.5N136.1W	
Sep 20	62	TS	Claudia	35	15.0N106.0W	27.4N114.7W	Onshore(020)
Sep 20	71	H	Olivia**	100r	14.0N91.6W	27.0N114.0W	Onshore(020)
Sep 21	55				19.1N108.7W	18.6N124.6W	
Sep 21	57	TS			20.6N108.0W	24.4N108.1W	
Sep 21	59	H		70r	16.0N118.9W	20.0N128.0W	
Sep 23	65	TS	Hazel	50	19.0N109.5W	23.5N106.3W	Onshore(070)
Sep 23	68	TS	Orla	35	17.0N109.5W	15.5N139.7W	
Sep 24	63	TS	Lillian	55	17.2N102.2W	22.9N108.1W	Onshore(060)
Sep 25	21				15.9N104.8W	31.8N116.7W	Onshore(020)
Sep 25	66	TS	Kirsten	55	18.0N114.5W	26.3N109.3W	
Sep 26	32				14.8N97.6W	31.0N114.8W	Onshore(330)
Sep 26	62	TS	Unnamed	60	17.0N109.0W	20.5N119.0W	
Sep 27	54				14.0N94.0W	19.0N104.4W	Onshore(340)
Sep 28	68	H	Pauline	100	14.5N101.5W	26.5N110.0W	
Sep 29	58	H		90	15.8N100.0W	24.0N111.0W	Onshore(340)
Sep 30	69	TS	Irah	40	16.0N112.0W	17.5N114.5W	
Oct 1	55				19.0N106.6W	23.2N109.4W	Onshore(330)
Oct 1	57	H		90	17.5N118.2W	24.9N112.2W	Onshore(040)
Oct 1	62	H	Doreen	90	14.0N104.3W	25.1N108.2W	Onshore(030)
Oct 2	61	TS	Pauline		No track, peripheral reports only		
Oct 3	61	TS	Rebecca		12.0N124.3W	15.0N133.5W	
Oct 4	66	TS	Lorraine	40	16.0N104.0W	18.3N102.8W	
Oct 4	68	H	Rebecca	90	13.0N97.0W	22.8N114.0W	
Oct 4	70	H	Patricia	95r	12.4N99.6W	18.9N131.4W	
Oct 5	67	TS	Olivia	110	13.0N108.0W	26.8N110.0W	
Oct 6	71	H	Priscilla	110r	10.4N90.0W	22.9N106.2W	Onshore(030)
Oct 8	69	H	Jennifer	45	14.0N102.5W	23.4N106.7W	Onshore(030)
Oct 12	23				12.0N92.0W	16.0N94.1W	Onshore(350)
Oct 14	22				15.9N112.0W	23.9N106.9W	Onshore(030)

DATE	YR.	CLASS	NAME	MAX	ORIGIN	END	REMARKS
Oct 14	58	TS		44	16.0N112.2W	16.0N125.0W	
Oct 14	67	H	Priscilla	80	12.5N101.7W	16.8N128.5W	
Oct 16	66	TS	Maggie	60	9.0N91.0W	20.0N104.8W	Onshore(320)
Oct 16	56	TS		33	17.2N115.0W	17.2N120.6W	
Oct 17	57	H		80	14.0N104.0W	21.5N105.9W	
Oct 17	63	H	Mona	100	14.5N110.5W	24.4N108.0W	
Oct 18	68	TS	Simone	45	13.5N91.5W	14.7N92.6W	
Oct 18	59	TS		50	19.0N111.0W	19.5N109.0W	
Oct 20	57	H		108	16.0N113.0W	23.1N106.2W	Onshore(040)
Oct 20	68	TS	Tara	30	13.0N105.0W	22.0N137.5W	
Oct 21	60	H	Hyacinth	60	18.1N104.0W	23.2N107.0W	
Oct 21	70	TS	Rosalie	40	15.0N115.9W	19.5N121.0W	
Oct 22	25				13.1N94.0W	20.0N105.5W	Onshore(360)
Oct 22	59	H		127	13.0N95.5W	19.0N104.3W	Onshore(050)
Oct 22	67	TS	Ramona	30	14.9N119.5W	23.5N147.7W	
Oct 26	54				13.0N90.0W	17.1N124.2W	
Oct 27	36				14.0N105.0W	22.0N107.3W	
Oct 28	71	TS	Ramona	25	10.9N101.1W	16.1N108.9W	
Oct 29	58	TS		47	19.0N108.8W	20.8N105.5W	Onshore(050)
Nov 1	70	TS	Selma	60r	14.5N108.5W	22.3N112.7W	
Nov 10	61	H	Tara	60	14.7N101.5W	17.6N101.4W	Onshore(350)
Nov 25	71	TS	Sharron	30r	10.0N99.0W	11.0N111.0W	Questionable

* The date is the day of cyclogenesis or the first day of discovery. Many storms before 1965 were not discovered until some unfortunate merchantman plunged into a fully developed storm. There has sometimes been a watch and wait tendency in recent years. Storms have sometimes not been taken into a warning status until unmistakable evidence of being well developed was found on satellite readout. Dates are therefore somewhat biased to reflect a point in development closer to the time of reaching tropical storm strength.

Storms were first named in 1960. A continuous alphabetic rotation was continued from year to year until 1966 when the present system of starting at the beginning of the alphabet each year, corresponding to the Atlantic system,was instituted.

A subscript r indicates reconnaissance aircraft estimates of maximum winds. Values without subscripts are ship reports not necessarily from the maximum wind area or at the time of maximum development. Many of these ship reports are received by mail and were not available for synoptic analysis. Only actual report values were used because of the uncertainty of maximum wind estimates appearing in official warnings.

Points of origin and ending are subject to the same problem as in determining the date of origin. Some bias to the westward of the true initial point is inevitable as is some bias to the east of the true end point.

The "onshore" remark indicates that the given end point was the location where the cyclone crossed the coastline and began rapid dissipation. The numbers in parentheses are the appropriate courses of the cyclone at the time they crossed the coast.

APPENDIX E

SOURCES OF CURRENT CLIMATOLOGY

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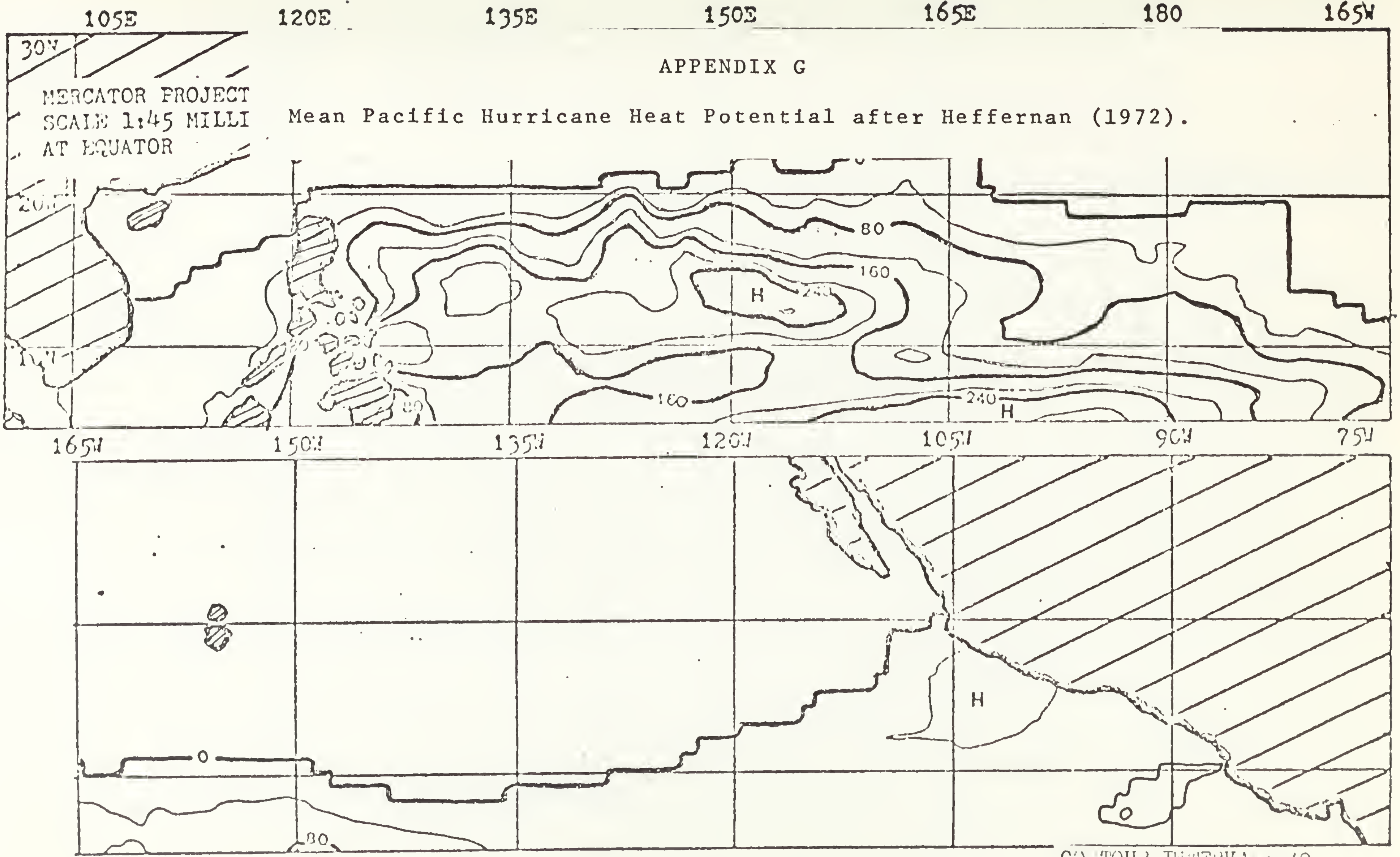
APPENDIX F

CIRCULAR DIAMETERS OF EASTROPAC TROPICAL CYCLONES

Date	Name	Location	Diameter	Remarks
23 Jun 67	H Carlotta	16.7N105W	3.6	
26 Jun 67	TS Francene	23.0N113.5W	3.0	
26 Jul 67	TS Georgette	16.0N128.5W	1.5	
9 Aug 67	TS Hilary	17.5N110.0W	3.0	Poor canopy
14 Aug 67	TS Ilsa	19.5N121.0W	4.9	
19 Aug 67	H Jewell	21.5N122.0W	3.0	
13 Sep 67	TS Lilly	19.5N125.5W	5.0	
13 Sep 67	TS Nanette	15.5N116.5W	4.2	
18 Sep 67	TS Monica	17.5N113.0W	3.0	
18 Sep 67	TS Nanette	20.5N129.0W	3.0	Edge of picture
11 Oct 67	H Olivia	17.5N113.5W	2.9	Poor canopy
13 Oct 67	H Priscilla	12.5N101.0W	4.2	
7 Aug 68	H Fernanda	15.0N118.0W	3.5	
31 Aug 68	H Liza	16.0N115.5W	3.0	
9 Oct 68	H Rebecca	17.8N104.6W	2.4	
Oct 68	TS Tara	Not known	4.3	
5 Aug 69	H Doreen	18.5N111.0W	3.7	
9 Sep 69	H Glenda	20.5N108.0W	3.0	
4 Sep 69	TS Florence	21.5N110.0W	2.7	
1 Oct 69	TS Irah	17.0N115.0W	2.5	
19 Sep 69	TS Heather	15.0N125.0W	2.6	
10 Oct 69	H Jennifer	20.0N108.0W	3.8	
1 Jun 70	TS Adele	11.0N107.5W	4.1	
17 Jul 70	TS Gretchen	18.0N117.5W	4.0	
17 Jul 70	TS Helga	18.0N108.0W	3.5	
31 Jul 70	TS Joyce	19.5N113.0W	3.0	
23 Aug 70	TS Maggie	14.8N144.5W	2.0	Ci. canopy open
22 Aug 70	H Lorraine	17.0N125.0W	3.6	
23 Aug 70	TS Lorraine	17.0N130.0W	4.8	
2 Sep 70	TS Norma	19.0N113.0W	4.0	
7 Oct 70	H Patricia	15.5N118.0W	4.3	
8 Oct 70	H Patricia	16.5N122.2W	3.4	
22 Oct 70	TD Rosalie	07.5N116.0W	2.3	
6 Jul 71	H Denise	12.0N117.0W	3.3	
7 Jul 71	H Denise	12.0N122.0W	3.3	
9 Jul 71	H Denise	14.0N134.5W	3.3	
19 Jul 71	H Francene	16.0N113.8W	2.0	Bright comma
24 Jul 71	TS Georgette	18.0N118.0W	3.7	
1 Aug 71	H Hilary	15.0N124.5W	3.3	
10 Aug 71	TS Katrina	20.0N107.0W	2.4	
31 Aug 71	H Monica	16.0N115.0W	3.3	
1 Sep 71	H Monica	18.0N115.0W	3.3	
25 Sep 71	H Olivia	17.0N108.0W	4.5	
9 Oct 71	H Priscilla	15.0N102.0W	3.3	

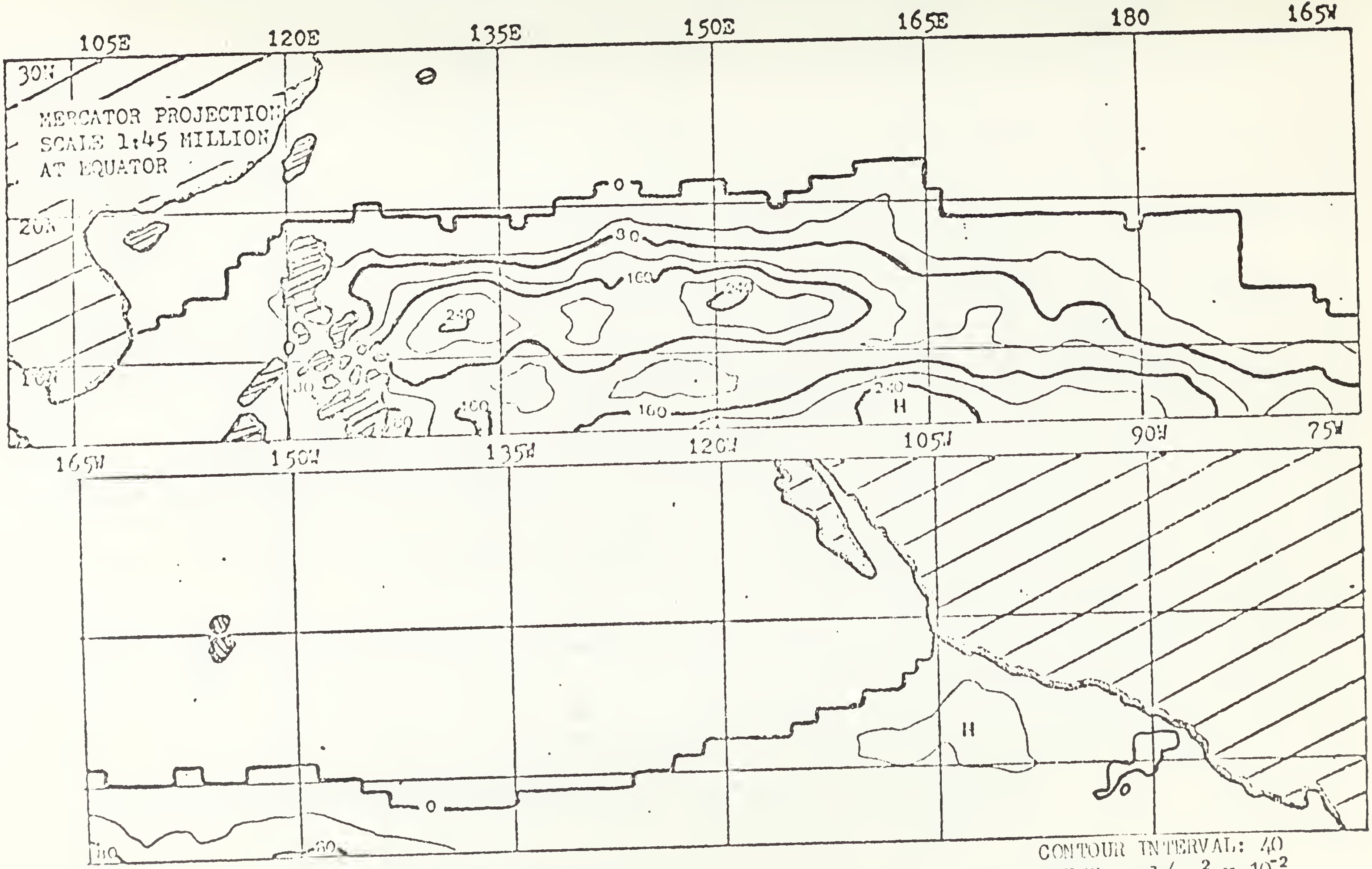
APPENDIX G

Mean Pacific Hurricane Heat Potential after Heffernan (1972).



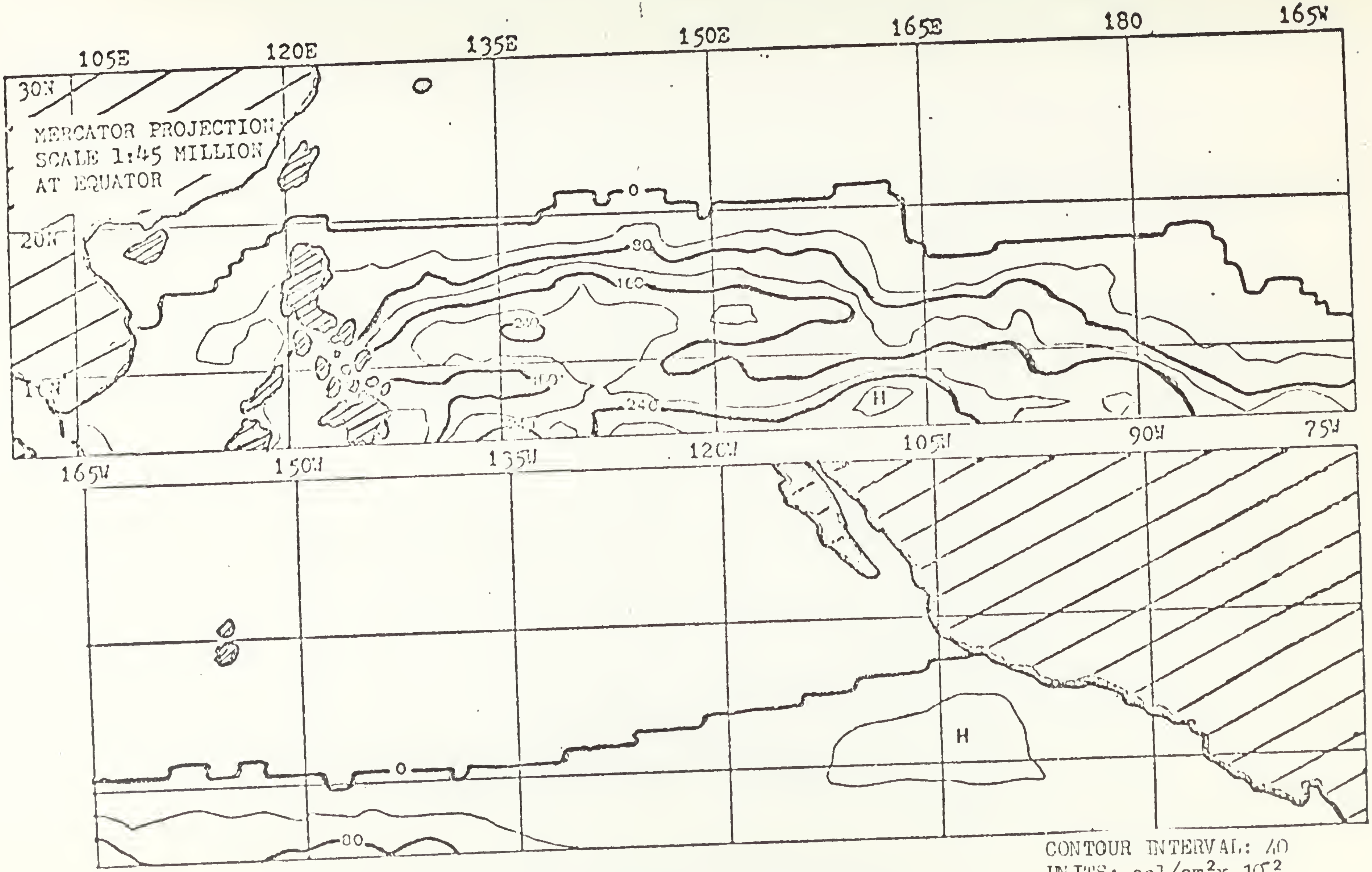
JANUARY MEAN HURRICANE HEAT POTENTIAL, NORTH PACIFIC.

CONTOUR INTERVAL: 40
UNITS: cal/cm²x 10^{-2}



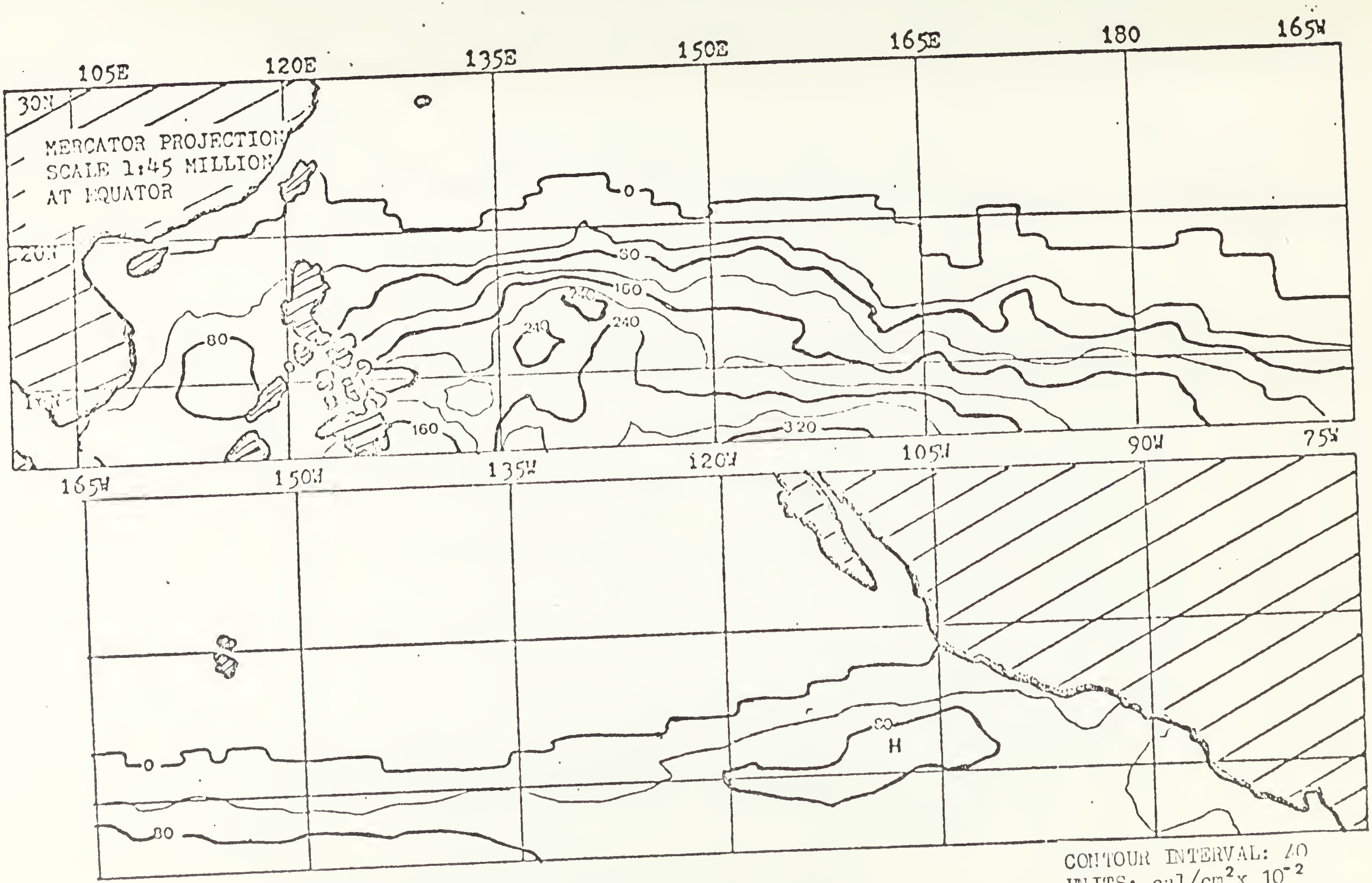
FEBRUARY MEAN HURRICANE HEAT POTENTIAL, NORTH PACIFIC.

CONTOUR INTERVAL: 40
UNITS: cal/cm^2 x 10^{-2}



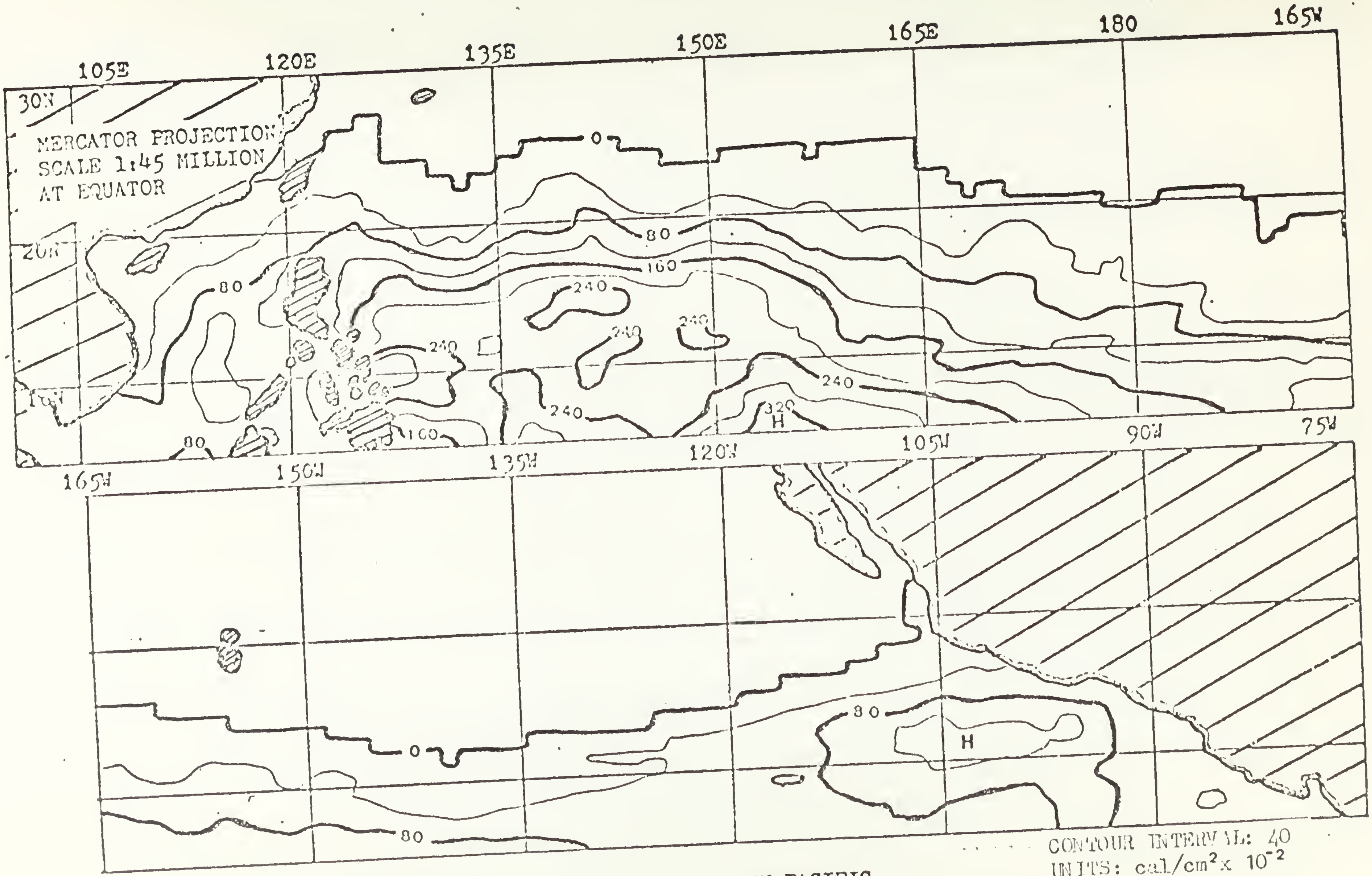
CONTOUR INTERVAL: 40
UNITS: cal/cm^{2}x 10^{-2}

MARCH MEAN HURRICANE HEAT POTENTIAL, NORTH PACIFIC.



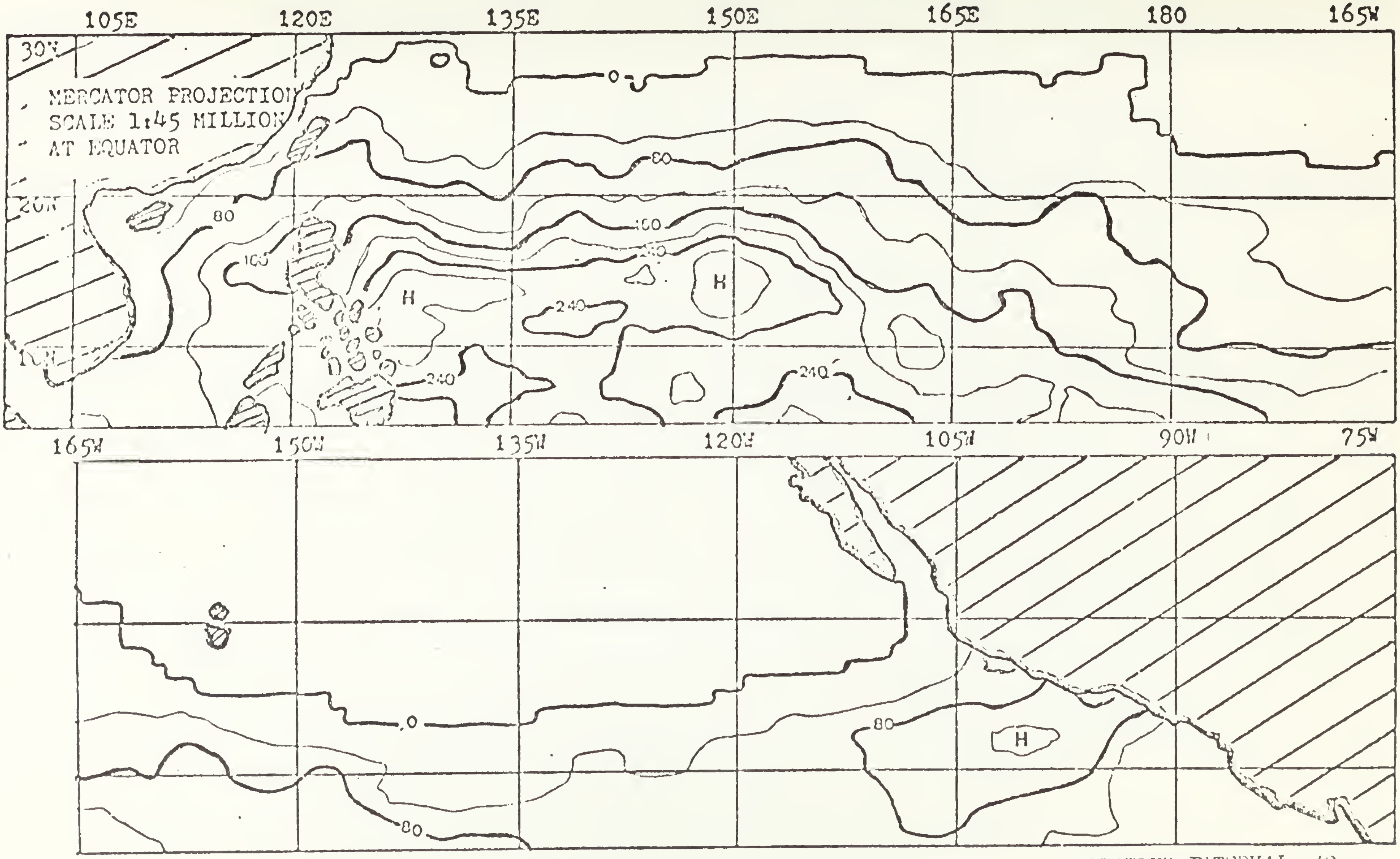
CONTOUR INTERVAL: 40
UNITS: cal/cm^{2}x 10^{-2}

APRIL MEAN HURRICANE HEAT POTENTIAL, NORTH PACIFIC.



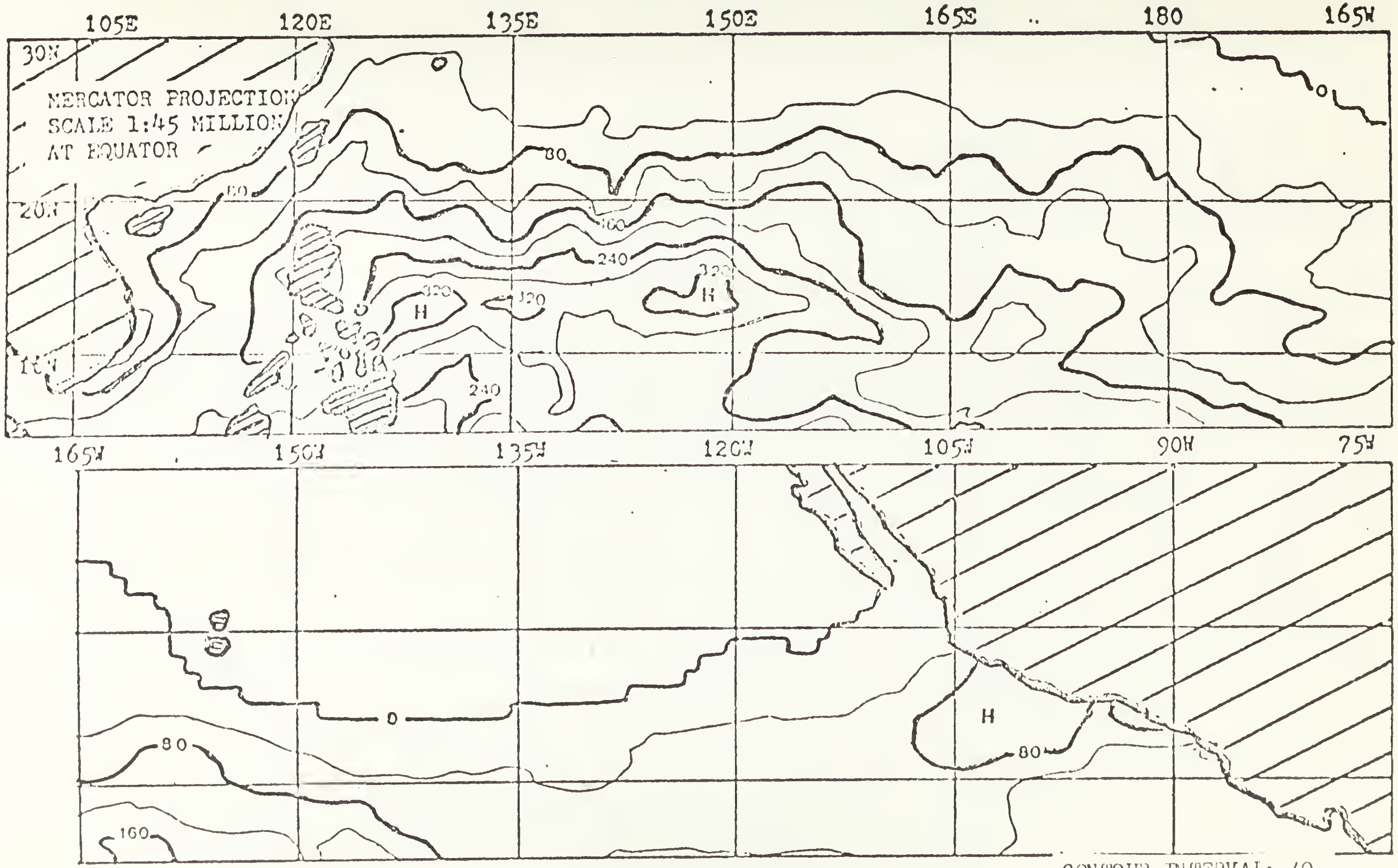
CONTOUR INTERVAL: 40
UNITS: cal/cm^{2}x 10^{-2}

MAY MEAN HURRICANE HEAT POTENTIAL, NORTH PACIFIC.

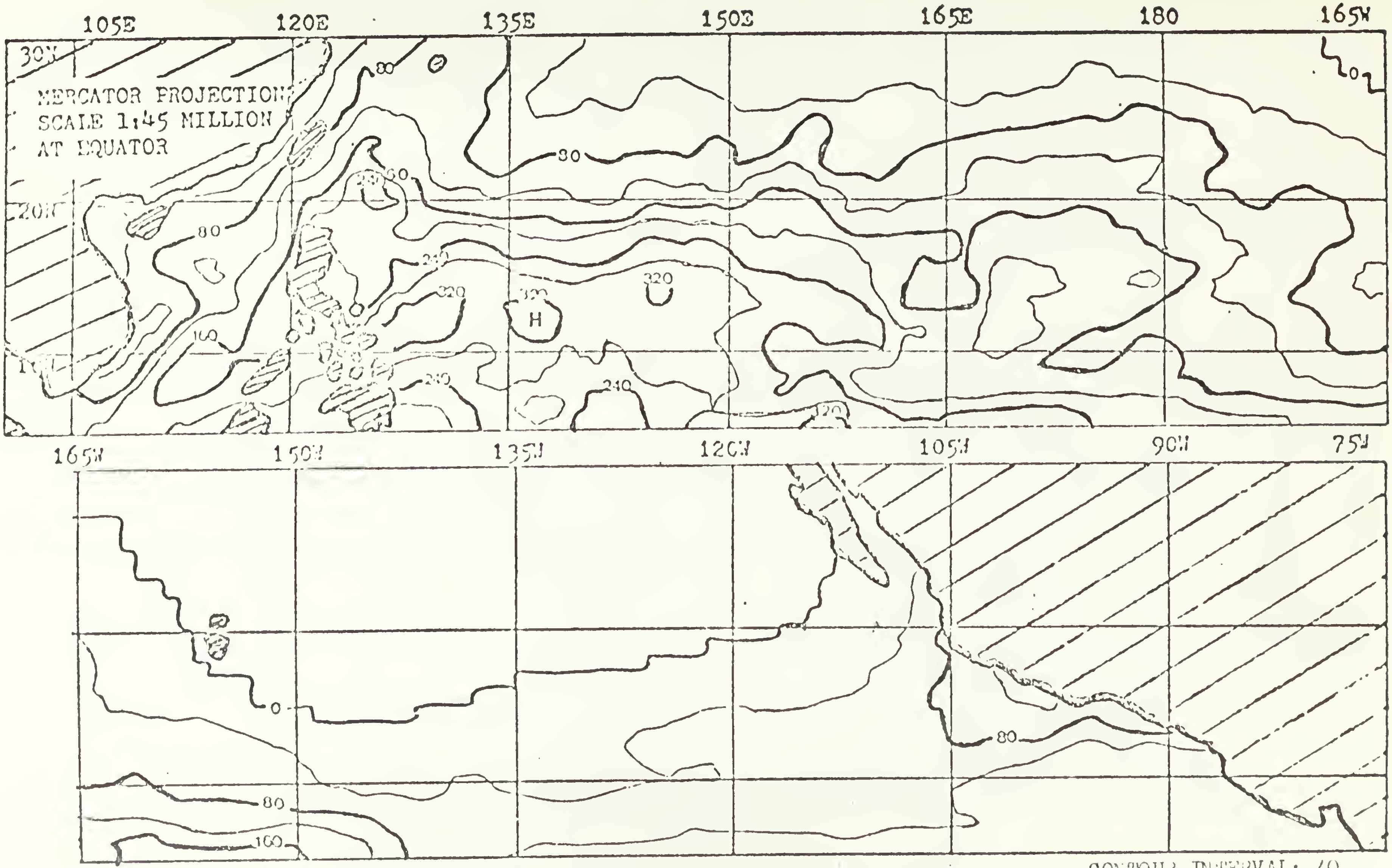


JUNE MEAN HURRICANE HEAT POTENTIAL, NORTH PACIFIC.

CONTOUR INTERVAL: 40
UNITS: cal/cm^2 x 10^{-2}

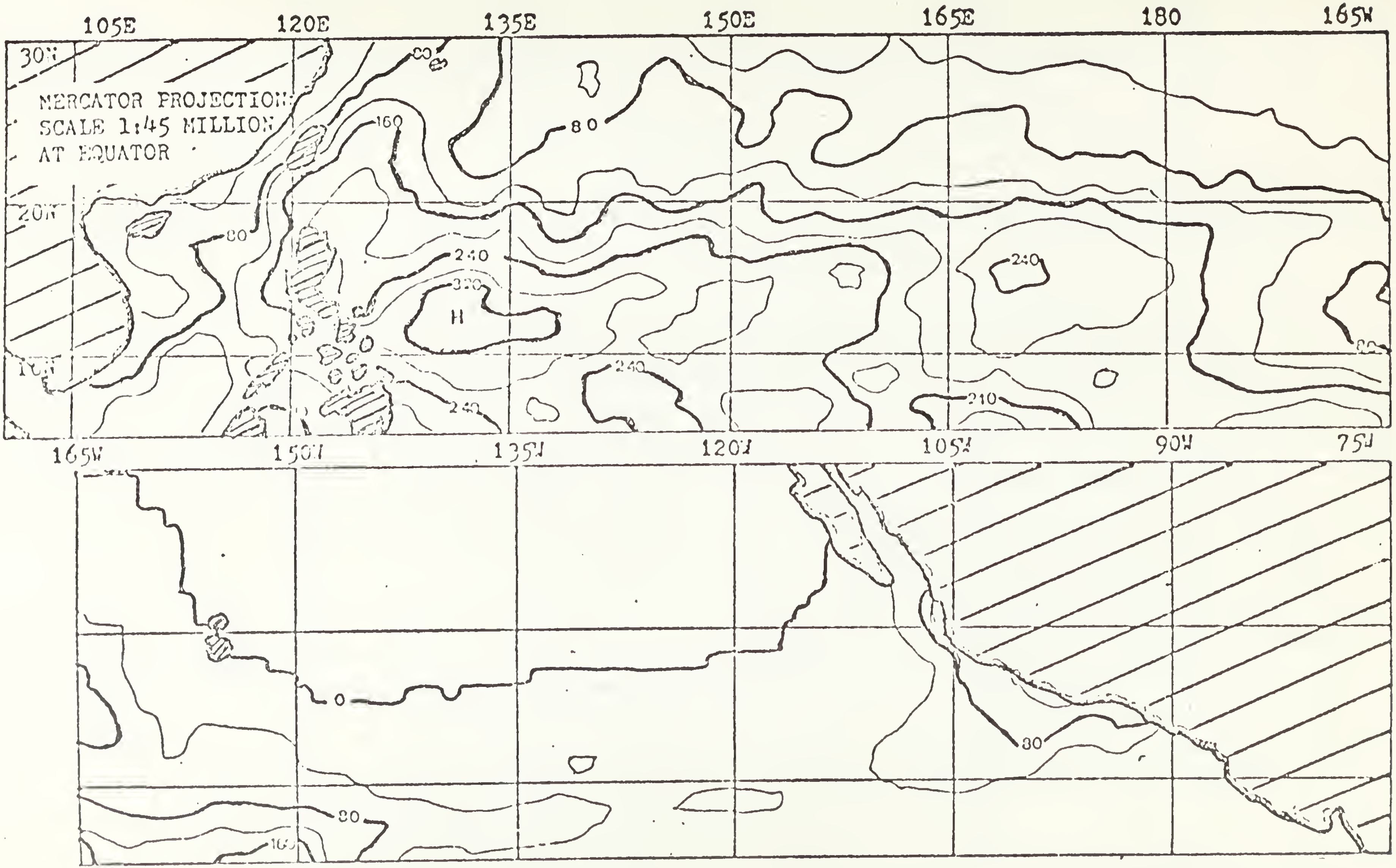


JULY MEAN HURRICANE HEAT POTENTIAL, NORTH PACIFIC.



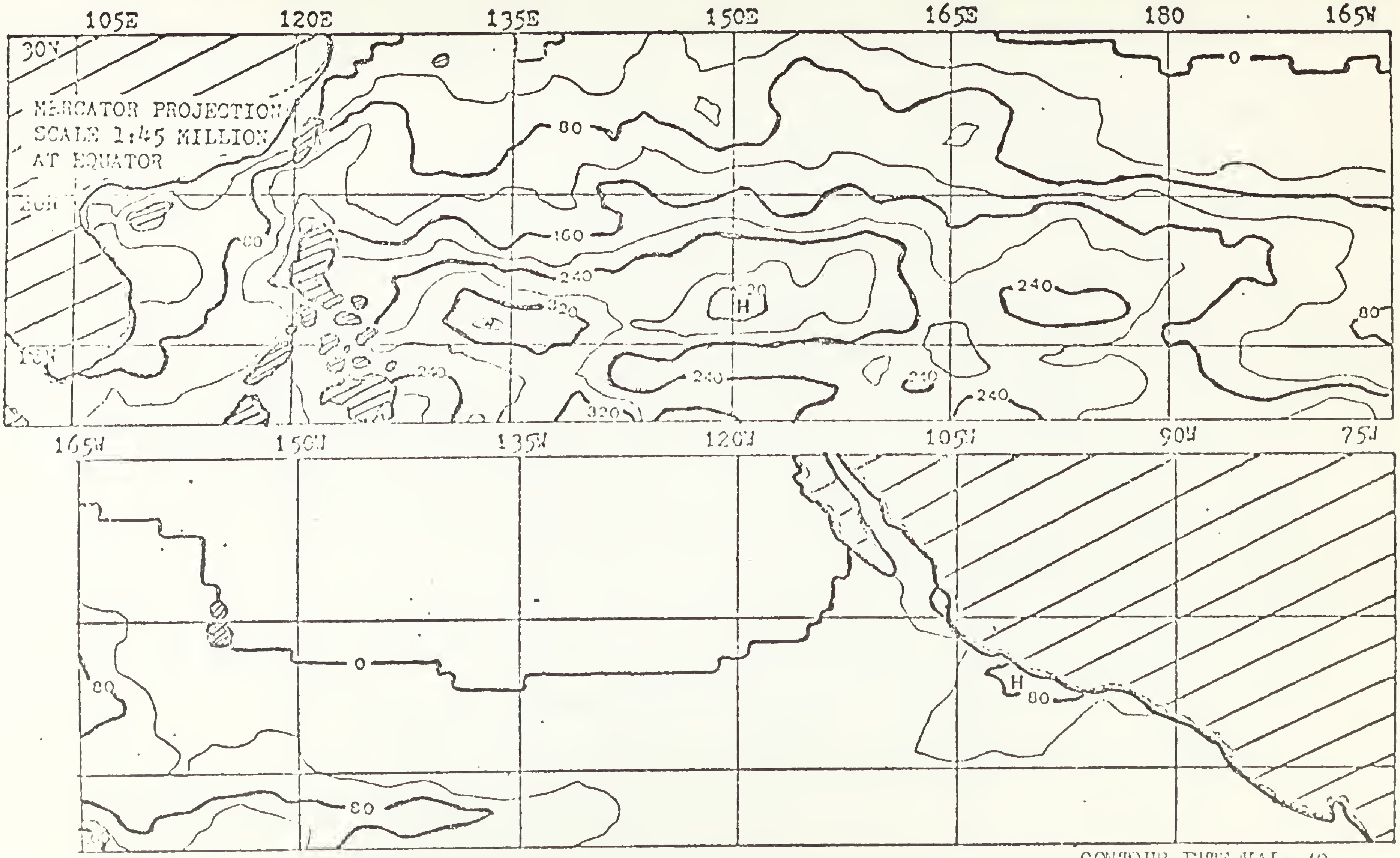
AUGUST MEAN HURRICANE HEAT POTENTIAL, NORTH PACIFIC.

CONTOUR INTERVAL: 40
UNITS: cal/cm^{2}x 10^{-2}



SEPTEMBER MEAN HURRICANE HEAT POTENTIAL, NORTH PACIFIC.

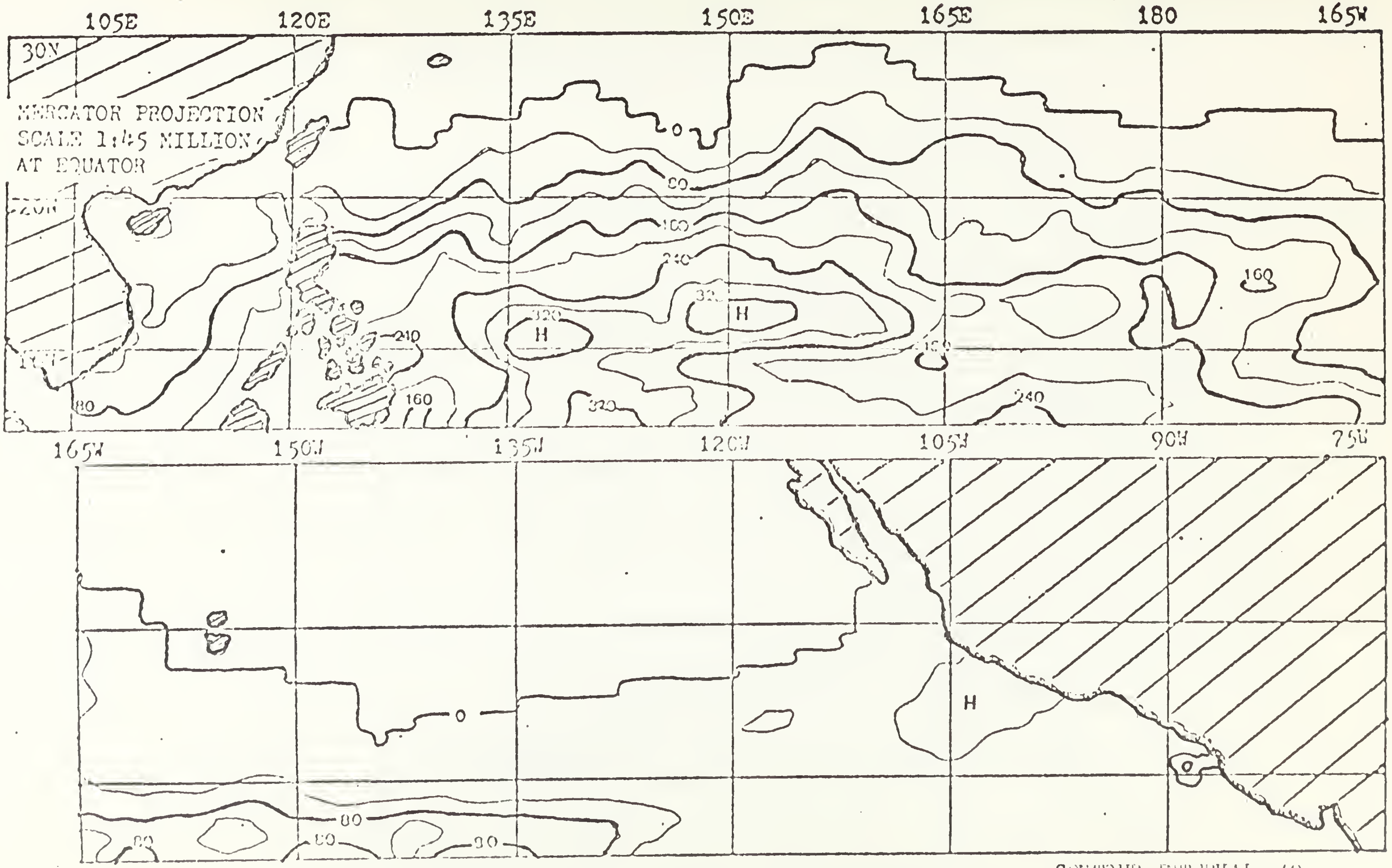
CONTOUR INTERVAL: 40
UNITS: cal/cm^2 x 10^{-2}



MERCATOR PROJECTION
SCALE 1:45 MILLION
AT EQUATOR

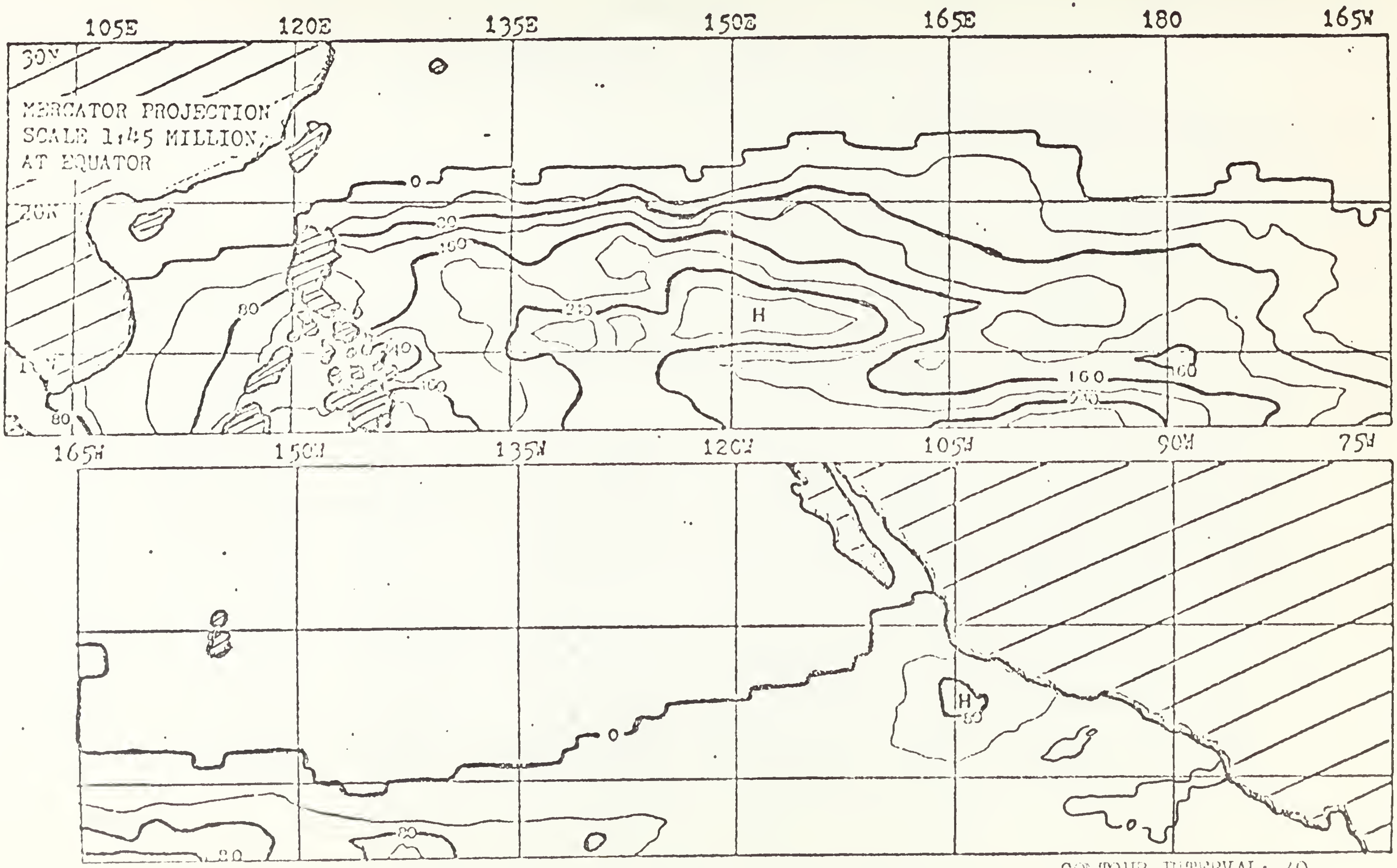
OCTOBER MEAN HURRICANE HEAT POTENTIAL, NORTH PACIFIC.

CONTOUR INTERVAL: 40
UNITS: cal/cm^{2}x 10^{-2}



CONTOUR INTERVAL: 40
UNITS: cal/cm^{2}x 10^{-2}

NOVEMBER MEAN HURRICANE HEAT POTENTIAL, NORTH PACIFIC.



DECEMBER MEAN HURRICANE HEAT POTENTIAL, NORTH PACIFIC.

CONTOUR INTERVAL: 40
UNITS: cal/cm^{2}x 10^{-2}

APPENDIX H

HUMP TRACKS 1956 - 1971

Year	Name	Dates	Origin	High point	Course	Dissipated	Distance
1956		8/22-25	16.0N114.0W	23.2N125.0W	253	20.6N131.5W	6.6
1958		9/6-12	16.5N109.0W	19.0N118.0W	260	17.0N130.0W	11.7
1959		7/22-25	14.0N120.0W	18.0N128.5W	258	17.0N134.0W	5.3
1963	TS Jennifer	9/12-15	16.0N110.2W	19.1N118.0W	258	18.0N123.0W	4.8
1965	TS Ava	6/28-7/5	08.0N87.0W	16.0N118.5W	254	14.7N123.3W	5.0
1965	TS Claudis	7/14	15.0N107.6W	18.5N119.5W	255	17.5N123.0W	3.6
1965	TS Doreen	7/28		20.0N116.0W	250	17.5N122.5W	6.5
1966	H Connie	8/7	14.0N122.0W	18.0N142.0W		16.0N156.5W	12.5
1966	H Francesca	9/5-11	15.0N106.0W	18.0N117.5W	253	14.0N130.0W	12.7
1968	TS Iva	8/21-27	15.8N107.0W	18.8N119.0W	258	15.2N138.0W	18.6
1969	TS Claudia	7/21	13.0N129.0W	16.0N135.0W	253	14.2N141.0W	6.0
1969	H Doreen	8/4	15.8N107.0W	21.7N118.0W	255	20.3N123.0W	4.9
1970	TS Gretchen	7/14-21	15.0N108.0W	19.0N119.5W	257	18.0N123.0W	3.4
1970	TS Joyce	7/29-8/4	18.0N107.0W	20.0N116.5W	260	19.0N122.0W	5.3
1971	H Denise	7/2-13	11.0N98.0W	18.1N146.2W		16.0N156.0W	9.8
1971	H Ilsa	7/30-8/8	12.0N98.0W	23.9N122.4W	250	22.0N128.0W	5.6
1971	H Nanette	9/2-9	12.0N95.0W	22.0N111.0W	262	21.0N118.0W	6.5

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13. ABSTRACT

Meteorological satellites have revealed the need for a major revision of existing climatology of tropical cyclones in the Eastern North Pacific Ocean. The years of reasonably good satellite coverage from 1965 through 1971 provide the data base from which climatologies of frequency, duration, intensity, areas of formation and dissipation and track and speed characteristics are compiled. The climatology of recurving tracks is treated independently.

The probable structure of tropical cyclones is reviewed and applied to this region. Application of these climatologies to forecasting problems is illustrated. The factors best related to formation and dissipation in this area are shown to be sea-surface temperature and vertical wind shear. The cyclones are found to be smaller and weaker than those of the western Pacific and Atlantic oceans.

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