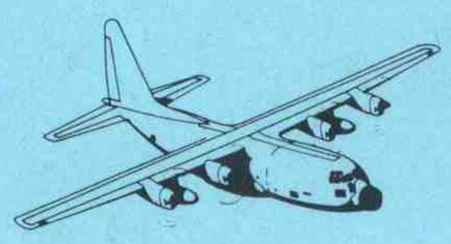
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METEOROLOGICAL SERVICES AND SUPPORTING RESEARCH

Tropical Cyclone Studies





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FEDERAL COORDINATOR
FOR
METEOROLOGICAL SERVICES AND SUPPORTING RESEARCH

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TROPICAL CYCLONE STUDIES

by

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FOREWORD

The Ad Hoc Group for Tropical Cyclone Studies was chartered by the Interdepartmental Committee for Meteorological Services and Supporting Research at the request of the Committee for Basic Services. The Ad Hoc Group at the 41st Interdepartmental Hurricane Conference, was tasked to

> Investigate the state of satellite tropical cyclone interpretation accuracies; plan, coordinate, and conduct a study of operational accuracies of satellite-based tropical cyclone estimates of positions, intensities, and wind-fields and prepare a report of the investigation.

A second task of the Ad Hoc Group was to

> Investigate the contribution of airborne weather reconnaissance in tropical cyclone forecasting; guide a study of tropical cyclone forecast accuracy based on non-airborne weather reconnaissance data; work in conjunction with the study on satellite tropical cyclone interpretation accuracies; and prepare a report of the investigation.

This report provides the results of the first task investigation and provides a statistical inference for the second task.

These studies were prepared with the cooperation of the directors or commanders and the staffs of the National Hurricane Center, Air Force Global Weather Central, the National Environmental Satellite, Data, and Information Service Satellite Analysis Branch, the Joint Typhoon Warning Center, and Headquarters, Air Weather Service. We thank them all for this effort and support.



Robert L. Carnahan
Federal Coordinator for
Meteorological Services
and Supporting Research

TROPICAL CYCLONE STUDIES

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PART 1

PRELIMINARY RESULTS OF A STUDY OF THE ACCURACY OF SATELLITE-BASED TROPICAL CYCLONE POSITION AND INTENSITY ESTIMATES

by

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1.1. Introduction. The 41st Annual Interdepartmental Hurricane Conference conducted in 1987 directed that the Office of the Federal Coordinator for Meteorological Services and Supporting Research conduct a study of the present-day accuracies of techniques utilizing meteorological satellite data for estimating tropical cyclone positions and intensities. The impetus for this study at this time was the budgetary constraints that forced a very serious look at the need for aircraft reconnaissance for tropical cyclones.

1.2. Background. A similar study was requested by the former Commander of the Air Weather Service (General Aldridge) and former Director of the National Hurricane Center (Dr. Neil Frank) in 1974 for making decisions on where and when to substitute satellite "fixes" for aircraft reconnaissance fixes. That study (Sheets and Grieman, 1975) provided information that could be used to evaluate risks to determine where and when satellite fixes were sufficient and where the more reliable aircraft reconnaissance fixes were required. This mix of satellite and aircraft reconnaissance positions had been used in the Atlantic and Western Pacific regions for several years prior to the study (Selective Reconnaissance Program) to minimize aircraft reconnaissance costs. However, aircraft reconnaissance fixes were used whenever possible for any critical forecast period. The purpose of the study at that time was to determine the degree of uncertainty associated with the satellite fixes for expansion of their exclusive use. The study involved several trained analysts from the U. S. Air Force (USAF) and the National Environmental Satellite Service (NESS) analyzing a large set of satellite pictures from polar orbiter satellites (DMSP and ESSA) and geosynchronous satellites (ATS) for determining the strength and locations of tropical cyclones. The study showed that intensity estimates (estimates of maximum sustained wind speed) on average differed by as much as 20 to 25 kt from the after-the-fact "best track" estimates 10 to 15 percent of the time. Mean position estimates deviated from the best track positions by an average of nearly 40 nmi for the "best satellite" estimates. Mean deviations from best track values for individual analysts ranged from 55 to 60 nmi with some much larger differences present.

1.2.1. The 1975 Study. The Sheets and Grieman study of 1975 utilized individual pictures analyzed after-the-fact. Operational conditions were simulated only in that pictures were given to the analysts one at a time with retention of past pictures. No other information was available to the

analysts such as surface observations, reconnaissance observations, or satellite animation. The exercise gave a true measure of internal uncertainties in satellite-based estimates but did not entirely simulate operational conditions. One major problem with a total operational simulation or actual evaluation is that the satellite estimates may be contaminated by other sources of information such as aircraft reconnaissance data. That is, one would not be able to obtain a true measure of accuracies that would be available with a satellite-only system unless the analysts were isolated from advisories or other information utilizing reconnaissance data.

1.2.2. Changes Since 1975. Several advancements in satellite data acquisition and display capabilities have been instituted since the time of the earlier study. One major operational capability advancement has been enhancement and animation of imagery as frequently as every 30 minutes. The Dvorak technique for estimating tropical cyclone intensities has also been modified during this period (Dvorak, 1984, 1987). Therefore, a re-evaluation of operational satellite-based intensity and position estimation techniques seems quite appropriate at this time.

1.2.3. Data Used in the Study. The study described in this paper utilizes data that were derived operationally in real time. That is, these were the actual values utilized by the National Hurricane Center (NHC) and the Eastern Pacific Hurricane Center (EPHC) in the preparation of their advisories and forecasts. In this situation, the satellite analysts had all sources of data available to them concerning the tropical cyclones including aircraft reconnaissance data and advisories as well as perhaps knowing what other satellite analysts had determined for previous fixes. Contamination from sources of data other than their independent satellite determined values is probably present most of the time and is clearly evident for some situations. Therefore, the values obtained in this study probably represent the best that could be expected for similar operational conditions without reconnaissance information. Comparisons of estimates with and without aircraft reconnaissance data show that at times the satellite-based estimates are much worse when no "calibration" from aircraft data was available. Comparisons were made between values obtained by satellite analysts using polar orbiter data with those using geosynchronous satellite data. Also, comparisons were made with the after-the-fact best track values as an attempt to estimate deviations from ground truth. These comparisons actually represent an incestuous relationship since the satellite determined values were utilized in determining the best track values. Because of that factor, these values again probably represent the best that can be obtained in a satellite-only system under similar conditions.

1.3. Methodology. The method used in this evaluation involved the comparison of Air Force Global Weather Central (AFGWC)-determined positions with those determined by the satellite sections of the NHC (Atlantic Basin sample) and the EPHC (Pacific sample). The AFGWC unit utilized polar orbiting satellite data while the NHC and EPHC satellite units utilized geosynchronous (GOES) satellite data, including animation. Further comparisons were made between the various units and the best track values.

These best track values are the after-the-fact position and intensity values determined by the NHC and EPHC hurricane forecast units utilizing all available data. Position and intensity estimates made by the NHC and EPHC units were obtained at regular intervals (generally three hours for EPHC and three to six hours for NHC). A linear interpolation between the NHC and EPHC fixes was used to arrive at a position or intensity corresponding to the time of the irregular time of the AFGWC fixes. A similar approach was made for comparisons with best track values where a linear interpolation along the best track was made to compare with the times of the satellite fixes. The stratification by tropical cyclone category was based on best track values.

1.4. Positions: Internal Consistency - AFGWC versus EPHC.

1.4.1. Tropical Depressions. Figure 1-1 depicts the deviations of the AFGWC satellite-determined positions from the EPHC satellite unit determined values for tropical depressions for the 1986 hurricane season. The columns represent values at 5 nmi intervals where the first column represents values of 0 to 4 nmi, the second column is 5 to 9 nmi, etc., and the last column represents values 100 nmi or greater. Note that large differences exist between values determined by the two units using different satellite platforms. Figure 1-2 depicts the same information as Figure 1-1 except in cumulative form. That is, more than 50 percent of the cases differ by more than 36 nmi and 10 percent of the cases by more than 100 nmi.

1.4.2. Tropical Storms. Figures 1-3 and 1-4 are the same as for Figures 1-1 and 1-2 except they are for tropical storm strength systems. Again, note the large differences, but, as expected, there is a trend toward smaller values than for the weaker systems. The mean is 8 nmi less than for tropical depressions and 50 percent of the cases differ by 30 nmi as compared to 36 nmi. Ten percent of the cases differ by 83 nmi as compared to more than 100 nmi for tropical depressions (Table 1-1).

1.4.3. Hurricanes. Figures 1-5 and 1-6 show values for tropical cyclones of hurricane strength or greater. The trend for smaller values continues for stronger systems with mean values now near 27 nmi and the 50 percent cumulative value difference of slightly more than 20 nmi and the 10 percent value near 53 nmi.

1.5. Positions: Internal Consistency - AFGWC versus NHC. Figures 1-7 through 1-12 show similar comparisons for the Atlantic Basin where the comparison is between AFGWC-determined positions and those determined by the satellite unit at NHC. Note that the mean values and distributions are quite similar for the Eastern Pacific and Atlantic Basin data sets (Table 1-1). The only apparent significant difference appears to be for the large misses for tropical depressions and tropical storms for the Eastern Pacific as compared to the Atlantic. Part of those differences may be explained by the presence of aircraft reconnaissance data for the Atlantic. This will be indicated later.

Table 1-1. Deviations (in nmi) of AFGWC satellite determined positions from EPHC (Eastern Pacific) and NHC (Atlantic) satellite unit determined positions. The 50% and 10% columns indicate deviation values exceeded by 50% and 10% of the cases, respectively.

	Eastern Pacific				Atlantic			
	Mean	S.Dev.	50%	10%	Mean	S.Dev.	50%	10%
Trop. Depressions	47	36	36	100	45	35	34	93
Trop. Storms	39	36	30	83	38	27	31	69
Hurricanes	27	17	20	53	28	20	23	55

1.6. Positions versus "Best Track."

1.6.1. Eastern Pacific. Figures 1-13 through 1-18 show the distribution of differences between the EPHC satellite unit determined positions and best track positions for the 1987 hurricane season. During the 1987 season, only the San Francisco EPHC satellite unit provided position estimates to the operational forecasters at EPHC. This also means that those were the only routine positions available for determination of the best track. Since the best track generally consists of a smooth fit to the existing data points, small deviations would be expected unless satellite positions were somewhat erratic. Satellite analysts generally plot a working track as a first guess in their position determination. This working track is also somewhat smooth unless overruled by specific cloud features for center determination. During initial stages, satellite determined positions are often erratic and then get more consistent as the tropical cyclone intensifies. These conditions are reflected in Figures 1-13 through 1-18. The mean deviations and standard deviations for this data set are significantly smaller than the differences of the AFGWC satellite unit determined values versus those determined by the EPHC satellite unit for the 1986 season (compare Table 1-1 with Table 1-2).

1.6.2. Atlantic Basin. Figures 1-19 through 1-24 show distributions for the the Atlantic Basin for a data set for the 1981 through 1986 hurricane seasons. These comparisons are identical to those for the Eastern Pacific Basin with the exception of the satellite derived positions provided by the NHC satellite unit are compared to the EPHC satellite unit. Also, additional position estimates were available from AFGWC and aircraft reconnaissance which certainly influenced the best track determination as well as some satellite determined positions as will be demonstrated later. The result is probably an offset of influences for deviations from the best track. That is, additional data sources in an isolated environment would likely result in larger deviations of the satellite determined positions from the best track positions. However, if there is some calibration of satellite positions taking place as a result of aircraft reconnnaissance fixes and advisory

positions, these deviations would be reduced. Those conditions are reflected in the fact that distributions in Figures 1-19 through 1-22 are similar to their counterparts for the Eastern Pacific except for hurricanes. In the hurricane case, there were more large deviations in the Atlantic as reflected by the means, medians and standard deviations (see Table 1-2).

1.6.3. Comparisons to "Best Track." Figures 1-25 through 1-30 reflect the deviations of tropical cyclone positions derived from polar orbiter satellites as compared to best track values. Note that a much larger scatter is shown for all tropical cyclone strength categories for the polar orbiter based positions as compared to the geosynchronous data. This is probably due to two factors. The first is that grids are often not as accurate for polar orbiter imagery over the open ocean where there are no nearby land features on which to anchor the grid. The second is that the geosynchronous data allow animation that permits an analysis of actual cloud motions as compared to an assumed cloud notice-based upon structure. However, one advantage that polar orbiter data has is a higher resolution, especially for nighttime imagery and at higher latitudes or other points away from the GOES sub-satellite point. That feature can result in a better definition of features, especially during the weaker phases of the tropical cyclone. Note that polar orbiter deviations from best track values (Table 1-2) are significantly smaller than comparable satellite-to-satellite-based estimates (Table 1-1) for tropical depressions; the differences decrease for tropical storms and become nearly equal for hurricanes.

Table 1-2. Deviations (in nmi) of EPHC, NHC and AFGWC satellite determined positions from associated best track positions. The 50% and 10% columns indicate deviation values exceeded by 50% and 10% of the cases, respectively.

GEOSYNCHRONOUS

	EPHC - Eastern Pacific				NHC - Atlantic			
	Mean	S.Dev.	50%	10%	Mean	S.Dev.	50%	10%
Trop. Depressions	24	22	17	55	23	19	18	48
Trop. Storms	26	22	20	55	22	19	17	45
Hurricanes	14	12	11	28	19	19	14	38

AFGWC - Atlantic - POLAR ORBITER

	Mean	S. Dev.	50%	10%
Trop. Depressions	36	25	29	66
Tropical Storms	34	23	30	68
Hurricanes	26	17	22	54

1.7. Positions: Visible versus Infrared. The resolution of visible spectra imagery from the NOAA GOES meteorological satellites is approximately four times that of the infrared spectra imagery on those same satellites (1 km versus 4 km at the subsatellite point). Thus, visible spectra imagery should result in better positioning of such features as tropical cyclones. Figures 1-31 through 1-36 depict the distributions of visible spectra satellite determined tropical cyclone center position deviations from best track positions for the Atlantic Basin for 1981 through 1986. Figures 1-31 through 1-42 show deviations for the same Atlantic Basin hurricane season period, but for infrared spectra determined positions versus best track values. Note the significantly larger deviations for the infrared sample compared to the visible sample. As shown earlier, the deviations from the best track values generally are much smaller for hurricanes compared to tropical depressions. That characteristic of these distributions is illustrated in both of these data sets, but note that even the deviations for tropical depression center determinations using visible imagery are still less than similar deviations for hurricanes using infrared imagery (see Table 1-3).

Table 1-3. Deviations (nmi) of NHC satellite determined tropical cyclone center positions from best track positions for the Atlantic Basin utilizing VISIBLE and INFRARED spectra data. The 50% and 10% columns indicate deviation values exoeeded by 50% and 10% of the cases, respectively.

	VISIBLE SPECTRA				INFRARED SPECTRA			
	Mean	S.Dev.	50%	10%	Mean	S.Dev.	50%	10%
Trop. Depressions	19	16	16	39	27	20	21	56
Tropical Storms	19	17	15	40	25	22	19	50
Hurricanes	16	14	13	32	22	23	15	49

1.8. Influences of Aircraft Reconnaissance.

1.8.1. Operational satellite analysts sometimes utilize aircraft reconnaissance data to calibrate their tropical cyclone center position determinations from satellite imagery. That is, when there is some ambiguity in where the low level center position is located, they will frequently utilize the aircraft reconnaissance determined positions to identify cloud features that they may follow for future position determinations. Of course, if a cloud center is clearly evident in the satellite imagery, the analyst will use that position rather than be influenced by the aircraft reconnaissance determined position. Figures 1-43 through 1-54 and Table 1-4 attempt to depict this calibration factor. Figures 1-43 through 1-48 depict distributions there visible spectra determinations were used during periods when aircraft reconnaissance data were and were not available within 6 hours of the time of the satellite-based position determination. Note that the

means and standard deviations are significantly smaller for tropical storms and hurricanes when reconnaissance data were available as compared to when it was not available. However, differences are larger for the data sample where aircraft reconnaissance data were available versus when it was not for the tropical depression category.

1.8.2. Figures 1-49 through 1-54 show comparable distributions for the infrared spectra data sample for the 1981 through 1986 Atlantic hurricane seasons. Note here the major reductions in the number of large misses for all tropical cyclone categories when reconnaissance data were available as compared to when it was not available. These differences are much larger than for the visible spectra data set and even carry through the tropical depression stage where there was a reversal for the visible spectra case. This condition is probably due to the fact that the higher resolution visible spectra data frequently showed distinct cloud features which were utilized in center determinations disregarding aircraft reconnaissance positions. By contrast, the infrared data set with its poorer resolution would likely have more ambiguous cases where the analyst would calibrate utilizing the aircraft reconnaissance data. These differences without aircraft reconnaissance data would likely be even larger than indicated for deviations from the actual center positions. This is due to the incestuous nature of the preparation of the best track which becomes heavily reliant upon the satellite determined positions when aircraft reconnaissance positions are not available.

Table 1-4. Deviations (nmi) of NHC satellite determined tropical cyclone center positions from best track positions for the Atlantic Basin utilizing and spectra data. The 50% and 10% columns indicate deviation values exceeded by 50% and 10% of the cases respectively.

	VISIBLE SPECTRA				INFRARED SPECTRA			
	Mean	S.Dev.	50%	10%	Mean	S.Dev.	50%	10%
No Recon LT 6 HRS								
Trop. Depressions	17	16	14	37	28	19	24	55
Tropical Storms	20	19	17	43	28	26	22	67
Hurricanes	19	16	17	39	35	36	21	85
Recon LT 6 HRS								
Trop. Depressions	23	17	19	43	26	22	21	54
Tropical Storms	19	14	14	38	21	15	17	43
Hurricanes	15	13	13	29	17	14	14	34

1.9. Intensity: Internal Consistency. The primary technique utilized throughout the world for estimating the intensity of tropical cyclones utilizing satellite imagery was developed by Dvorak (1984). This technique, with some slight variations, is utilized by the satellite units at the NHC, EPHC, and AFGWC. The Dvorak technique results in a Current Intensity (C.I.) number that is related to the estimated minimum sea level pressure and maximum wind speed. Figures 1-58 through 1-60 show the intensity estimate differences between those obtained by the AFGWC and NHC satellite units for the 1981 through 1986 hurricane seasons. A larger range of differences is noted for all three tropical cyclone categories for the Atlantic Basin set as compared to the Eastern Pacific set. This may indicate some influence of aircraft reconnaissance observations in the Atlantic. Both the Atlantic Basin and Eastern Pacific data sets indicate the AFGWC unit had a slight bias toward underestimates of strength relative to the NHC and EPHC satellite units.

1.10. Intensity versus Best Track.

1.10.1. AFGWC Figures 1-61 through 1-63 show the intensity estimate differences between the AFGWC satellite unit derived values and those estimated for the best track for the Atlantic data set. These differences are displayed in terms of wind speed in knots at 5 kt intervals with the bar graphs centered on even 5 kt values. The abscissa represents AFGWC estimates minus best track values. Very little bias is noted versus best track values for tropical depression strength systems, but relatively large underestimate biases are noted for tropical storms and hurricanes.

1.10.2. NHC Figures 1-64 through 1-66 depict intensity estimate differences between the NHC satellite unit derived values and best track values. Only small biases are noted here relative to "best track" values, but rather large differences are present. These differences range up to + or - 35 kt for some hurricanes. That means you could have a satellite estimate of just barely a tropical storm (35 kt) and actually have a full fledged hurricane (70 kt) or vice versa. At the other end of the scale, you could have a satellite estimate of a Category 1 hurricane and actually have a Category 3 hurricane (on the Saffir-Simpson scale) or vice versa.

1.10.3. EPHC Figures 1-67 through 1-69 show the distribution of intensity estimate differences between the EPHC satellite unit values and best track values for the 1987 Eastern Pacific hurricane season. As mentioned earlier, the only position and intensity estimates routinely provided for the Eastern Pacific during the 1987 season were those provided by the EPHC satellite unit. That fact is well illustrated in these difference distributions where esentially no biases are shown and the great majority of the cases show exact agreement between the satellite derived value and the "best track" value. This of course does not reflect reality, but the necessary incestuous nature of the best track determination process. The only time there is likely to be differences between best track and satellite derived values is when a ship report might be received from the core of the hurricane (a rare occurrence) or if satellite estimates become erratic.

1.10.4. Summary. Comparisons of figures 1-61 through 1-69 strongly illustrate the probable underestimation of the uncertainties in satellite-based intensity estimates and their variations for many regions of the world. That is, because of lack of ground truth, best track values often simply reflect the satellite determined values themselves. This condition is illustrated in Table 1-5 when comparing Atlantic Basin difference values with those for the Eastern Pacific Basin.

Table 1-5. Deviations (kt) of satellite determined intensity estimates from best track values

	TROP. DEPRESSIONS		TROP. STORMS		HURRICANES	
	Mean	S.Dev.	Mean	S.Dev.	Mean	S.Dev.
Atlantic 1981-1986						
AFGWC - "best track"	+1.6	8.0	-7.4	10.7	-9.2	16.6
NHC - "best track"	+2.4	5.2	-2.0	8.1	-3.0	12.6
NHC - "best track" (no recon LT 6 hrs)	+2.5	4.9	-0.9	8.1	-2.2	9.6
NHC - "best track" (recon LT 6 hrs)	+2.1	5.7	-3.0	8.0	-3.2	13.2
E. Pacific 1987						
EPHC - "best track" (no recon)	+0.2	1.9	0.0	3.4	+0.9	4.9

1.11. Intensity: Impacts of Aircraft Reconnaissance. Figures 1-70 through 1-75 show the distritution of the NHC satellite unit intensity estimates versus best track values for the Atlantic Basin for periods when aircraft reconnaissance data were and were not available within six hours of the time the estimates were made. Note the lack of bias for tropical depressions and tropical storms for the no reconnaissance situation as compared with a small underestimate bias for the situation where reconnaissance data were available. The greatest differences for these two data sets, however, occurs with hurricane strength systems. This comparison shows that the number of cases differing by more than 10 kt from best track values is considerably larger for the sample with reconnaissance data as compared for the cases without it. Even more dramatic are the differences between these distributions and those shown for the Eastern Pacific data set (Figures 1-67 through 1-69) where no reconnaissance data and only one source of satellite-based estimates were available (also see Table 1-5).

1.12. Errors. The values presented throughout this paper probably represent the lower bound on errors that can be expected operationally from the present satellite-based system without aircraft reconnaissance. That is, present operational satellite position and to a lesser degree intensity estimates are sometimes calibrated directly by reconnaissance observations or through advisory information. This calibration factor for positions is partially shown in Figures 1-43 through 1-54 and Table 1-4. Similar biases in data are shown for a study involving Western Pacific data by Martin and Gray (1981) presented at 42nd Interdepartmental Hurricane Conference. Also, Figures 1-67 through 1-69 and Table 1-5 illustrate the false impression of accuracy that prevails in some areas where reconnaissance data are not available for ground truth. That is, the best track data are almost totally dependent upon the satellite-based estimates in those regions. In those cases, all that is obtained is a measure of the internal consistency of the satellite estimates.

1.13. Summary.

1.13.1. Differences between tropical cyclone center positions determined by the Air Force Global Weather Central satellite unit using polar orbiting satellite data and those obtained using geosynchronous satellite data were nearly the same for the Atlantic and Eastern Pacific Basins (Table 1-1). These satellite-determined position differences are largest for weaker systems and decrease in the mean as these tropical cyclones become stronger. However, large differences still were observed for tropical cyclones of hurricane strength with more than 10 percent of the cases exceeding differences of 50 nmi. Comparisons with after-the-fact "best track" values also indicated that, in the mean, positions determined from the polar orbiter satellites were inferior to those obtained from geosynchronous satellite data sources (Table 1-2). In the mean, these differences were approximately 10 nmi larger than for the geosynchronous data.

1.13.2. Intensity estimates made by different satellite units also showed relatively large differences. Differences between AFGWC-determined values and those from the NHC and EPHC satellite units ranged up to two (C.I.) numbers. This equates to possible wind speed estimate differences of as much as 50 kt. Comparisons with best track values resulted in difference ranges of up to 35 kt. This of course means that you could think you have a minimal hurricane (Category 1 on Saffir/Simpson scale) and actually have a Category 3. The difference in damage potential for such a situation of course is magnified by the fact that the force exerted by the hurricane is at least a function of the square of the wind speed (water loading could actually increase that force). Also, potential storm surge differences between a Category 1 and a Category 3 hurricane can be quite large, resulting in differences of evacuation requirements for several thousand people for selected portions of the U. S. coastline.

Acknowledgement. The authors wish to gratefully acknowledge the assistance of Robert A. Case and Dr. Arthur Pike for assimilation of some of the data. Also, considerable assistance was received from the Hurricane Research Division of the Atlantic Oceanographic and Meteorological Laboratory for preparation of the graphics.

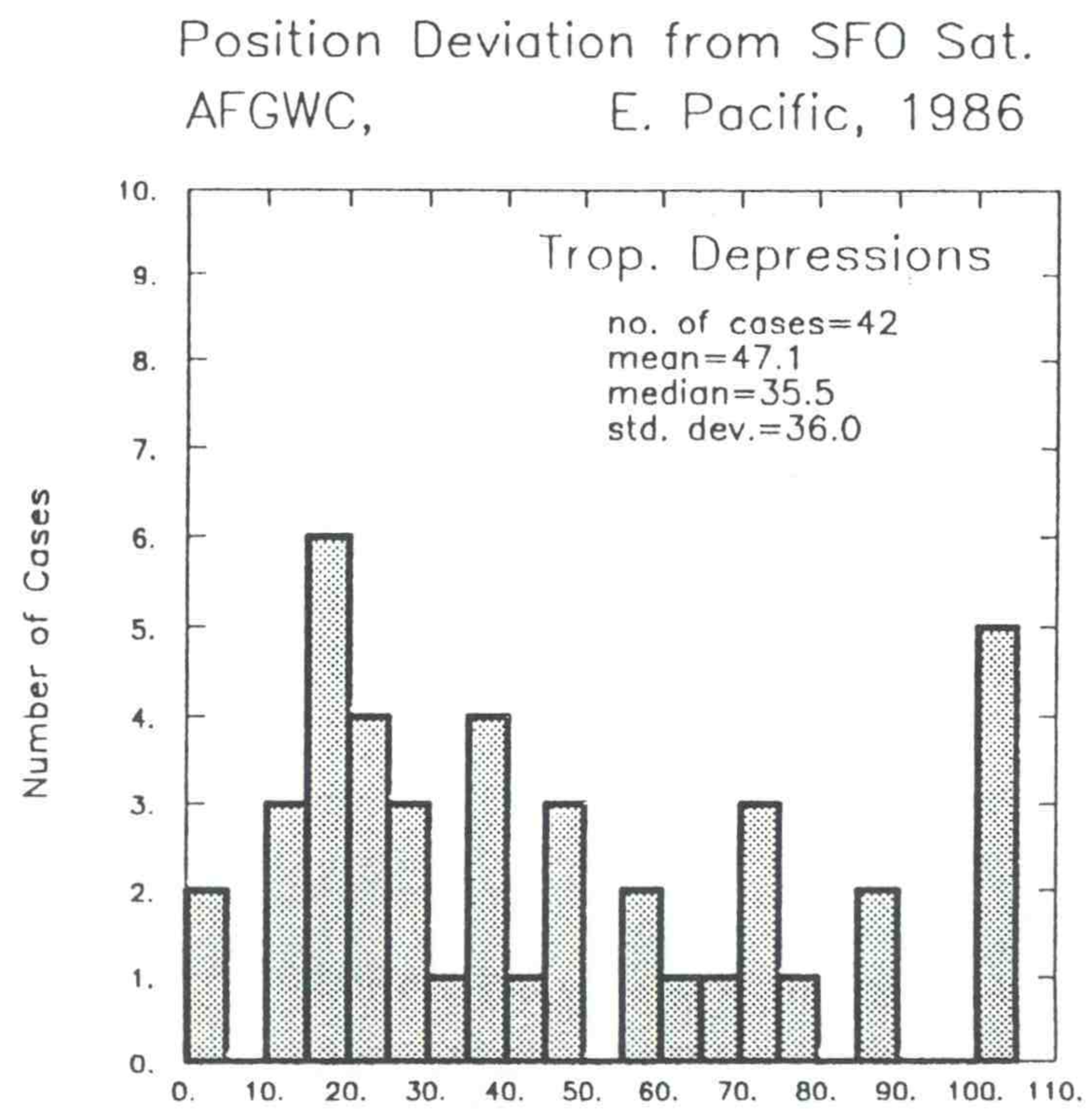


Figure 1-1. Deviations (in nmi) of AFGWC-determined positions from EPHC-determined positions for tropical depressions for the 1986 Eastern Pacific hurricane season--by number of cases.

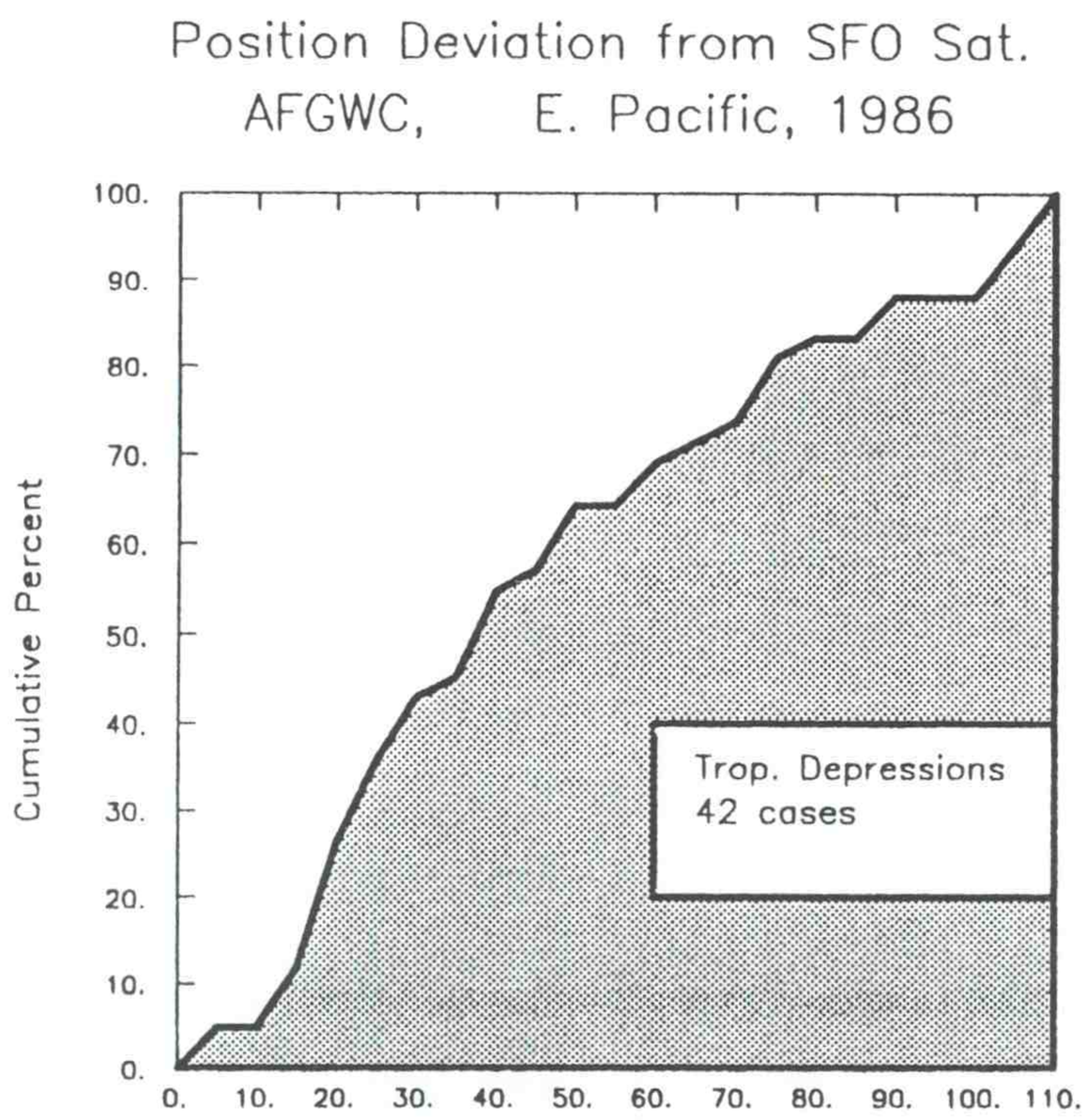


Figure 1-2. Deviations (in nmi) of AFGWC-determined positions from EPHC-determined positions for tropical depressions for the 1986 Eastern Pacific hurricane season--cumulative percentage.

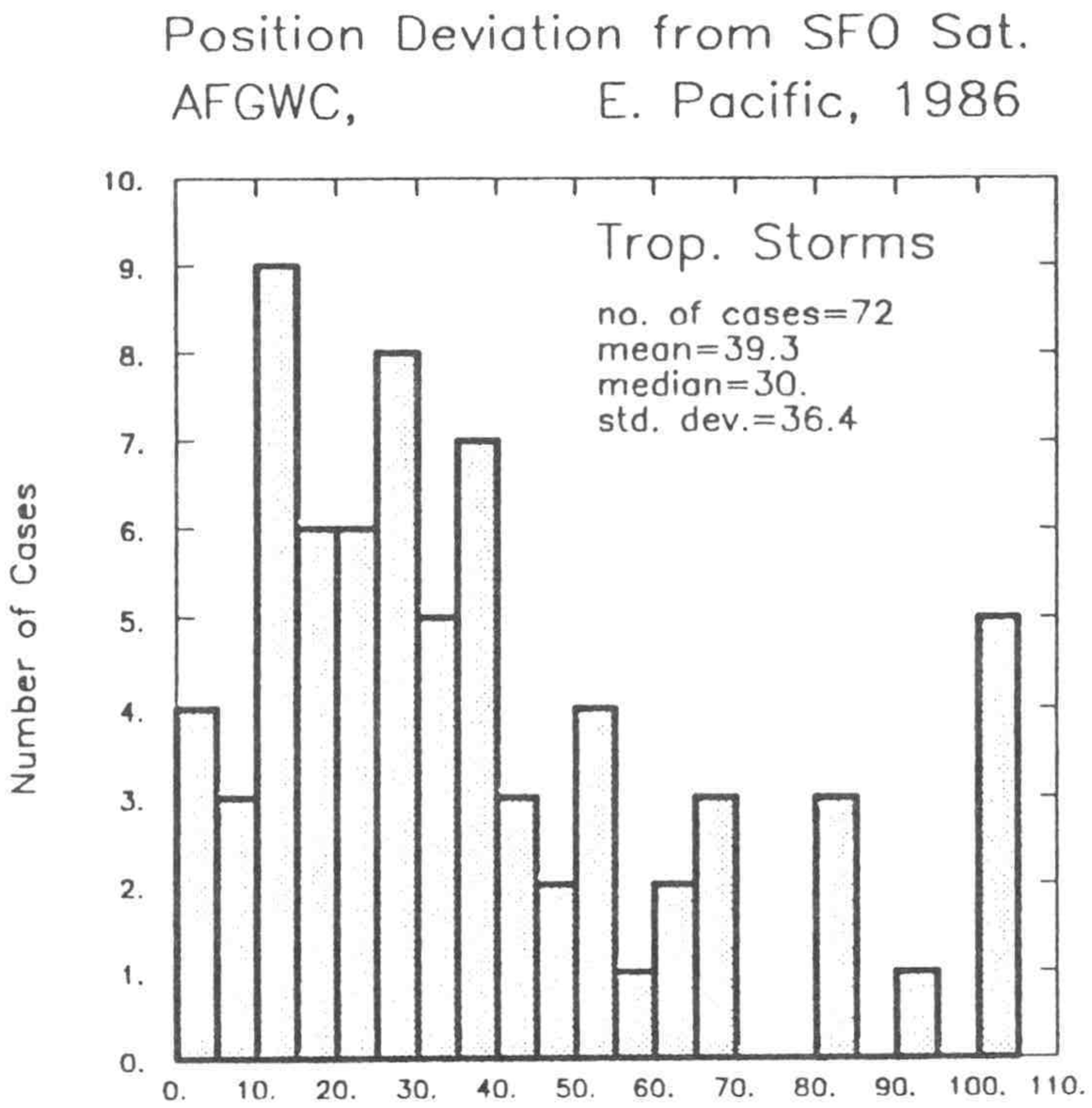


Figure 1-3. Deviations (in nmi) of AFGWC-determined positions from EPHC-determined positions for tropical storms for the 1986 Eastern Pacific hurricane season--by number of cases.

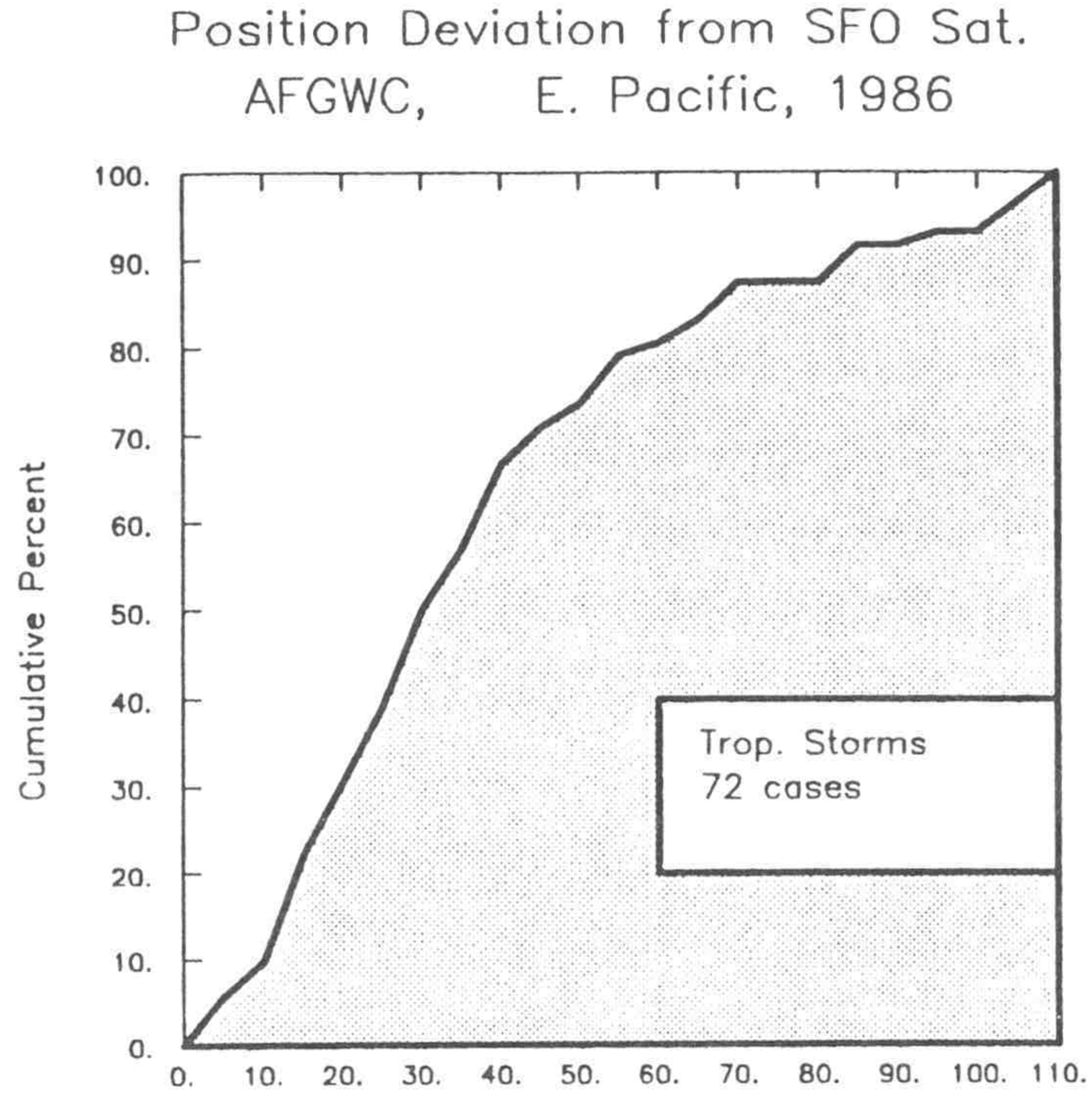


Figure 1-4. Deviations (in nmi) of AFGWC-determined positions from EPHC-determined positions for tropical storms for the 1986 Eastern Pacific hurricane season--cumulative percentage.

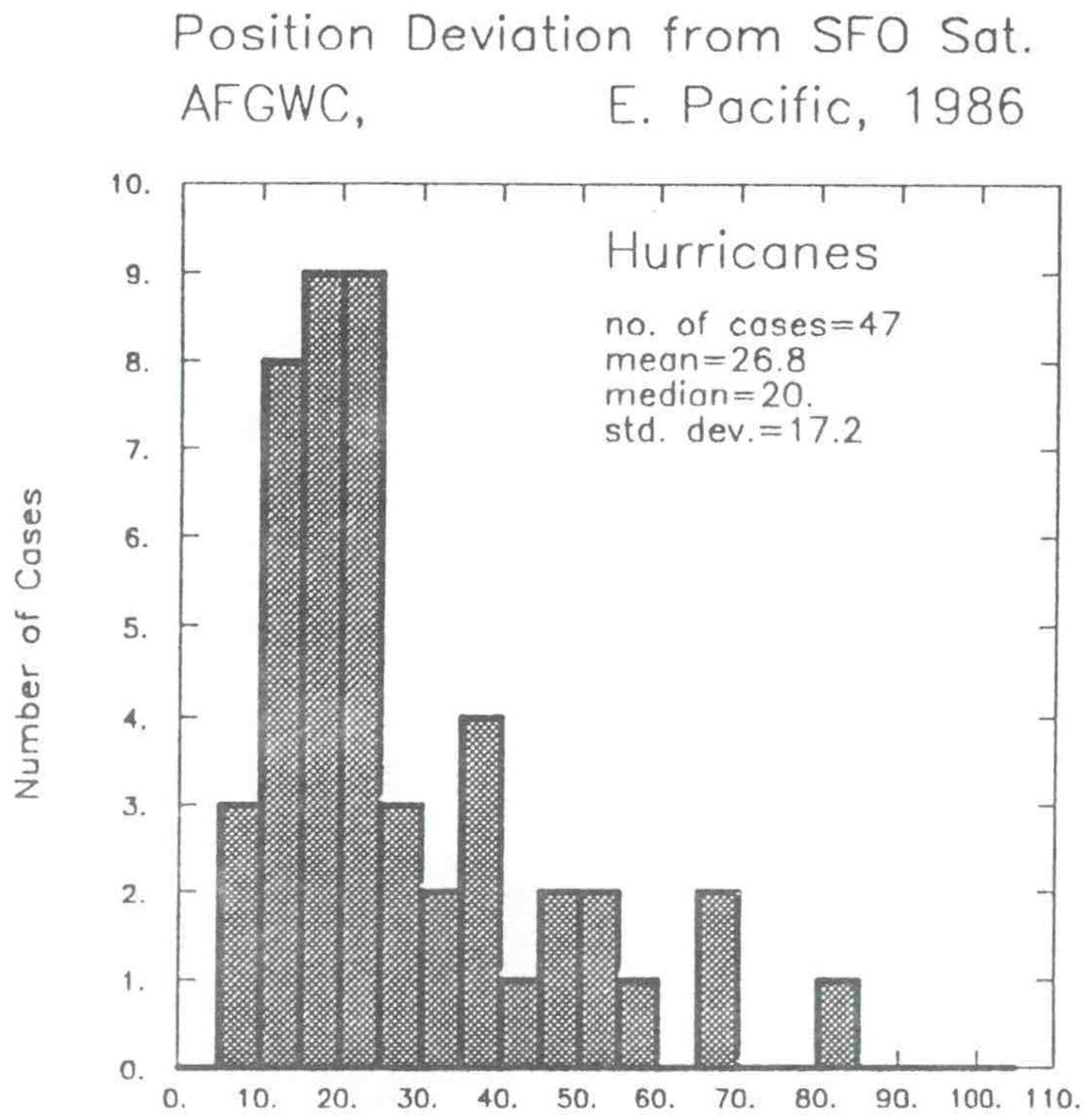


Figure 1-5. Deviations (in nmi) of AFGWC-determined positions from EPHC-determined positions for hurricanes for the 1986 Eastern Pacific hurricane season--by number of cases.

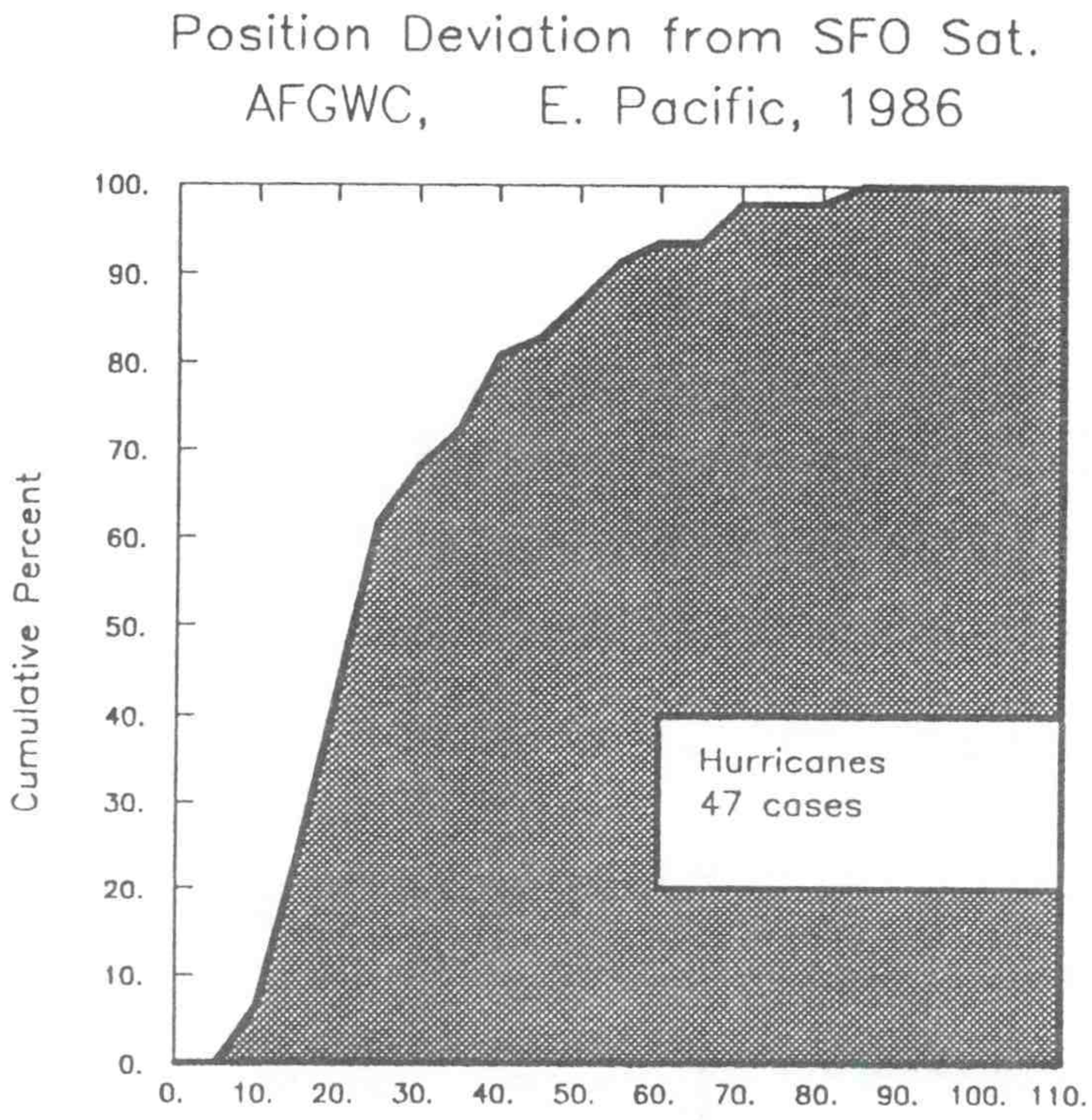


Figure 1-6. Deviations (in nmi) of AFGWC-determined positions from EPHC-determined positions for hurricanes for the 1986 Eastern Pacific hurricane season-- cumulative percentage.

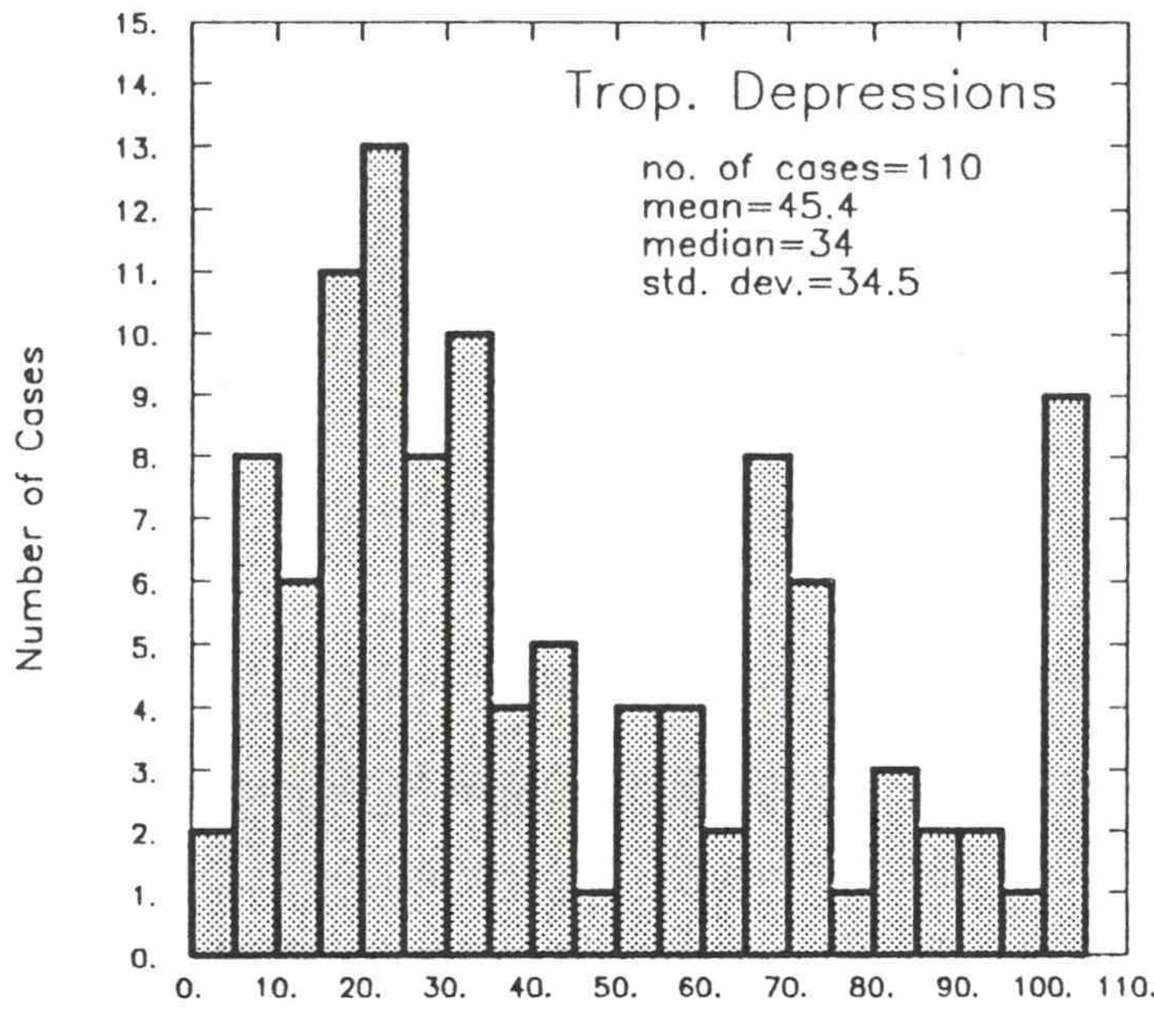


Figure 1-7. Deviations (in nmi) of AFGWC-determined positions from NHC-determined positions for tropical depressions for the 1981-86 Atlantic Basin hurricane season--by number of cases.

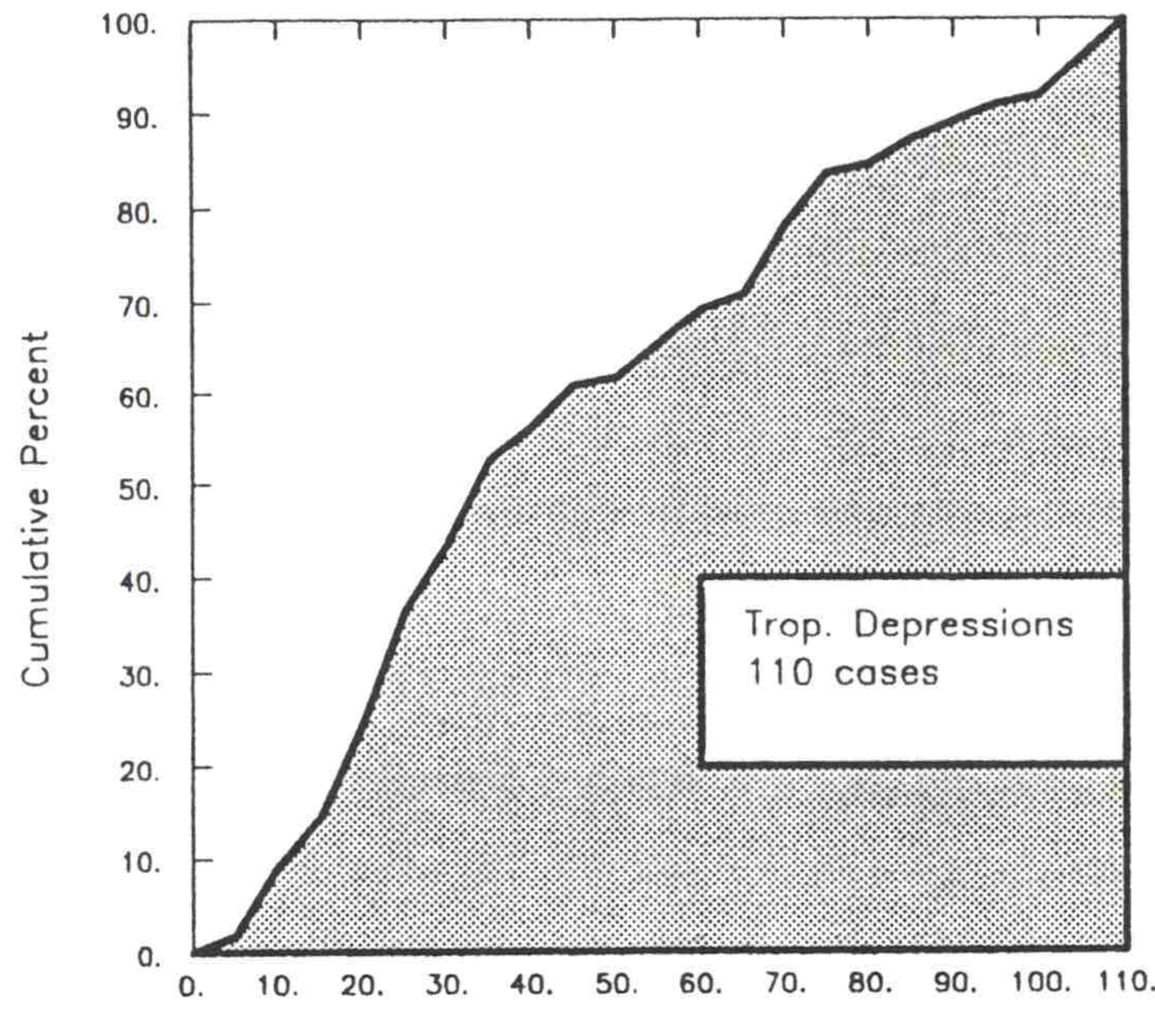


Figure 1-8. Deviations (in nmi) of AFGWC-determined positions from NHC-determined positions for tropical depressions for the 1981-86 Atlantic Basin hurricane season--cumulative percentage.

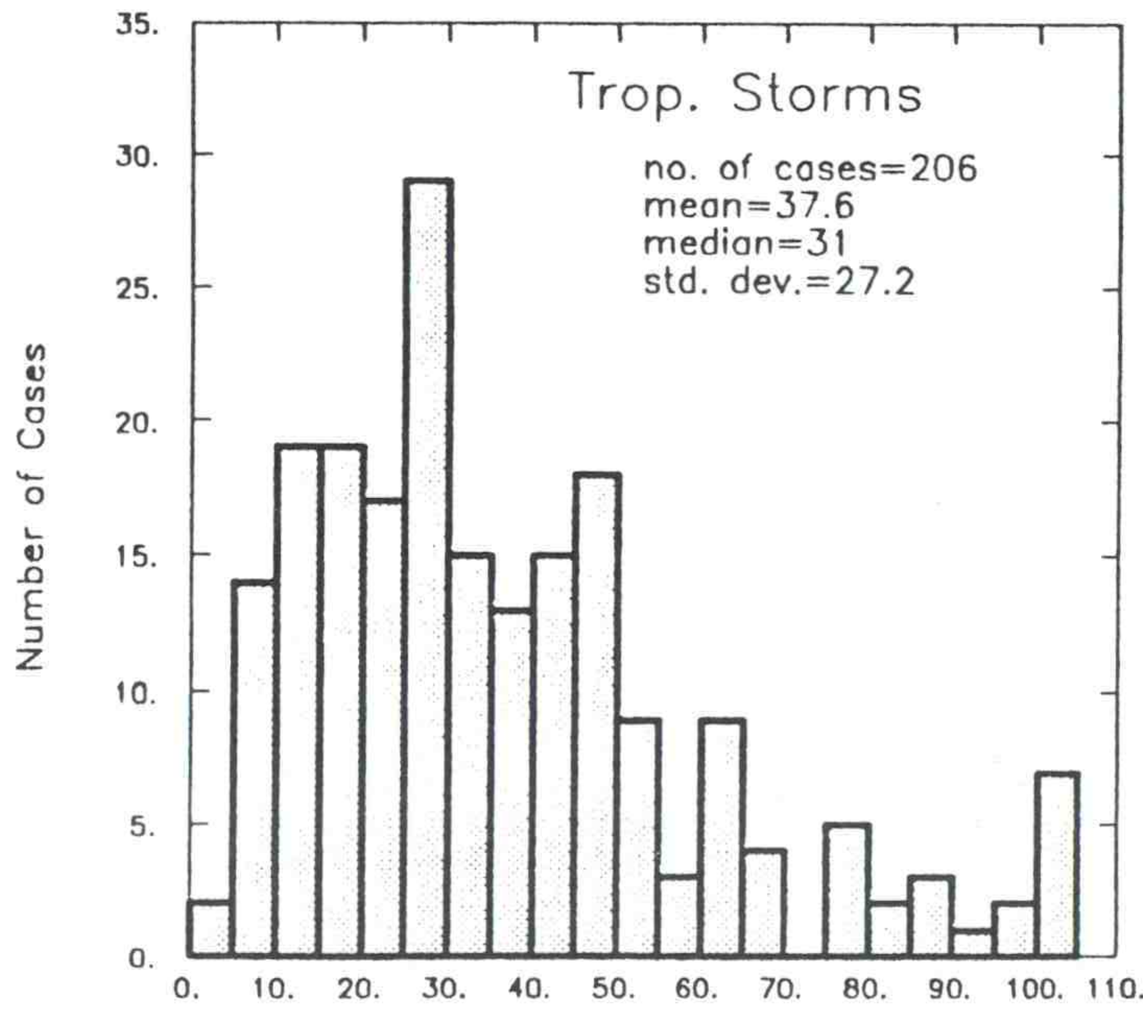


Figure 1-9. Deviations (in nmi) of AFGWC-determined positions from NHC-determined positions for tropical storms for the 1981-86 Atlantic Basin hurricane season--by number of cases.

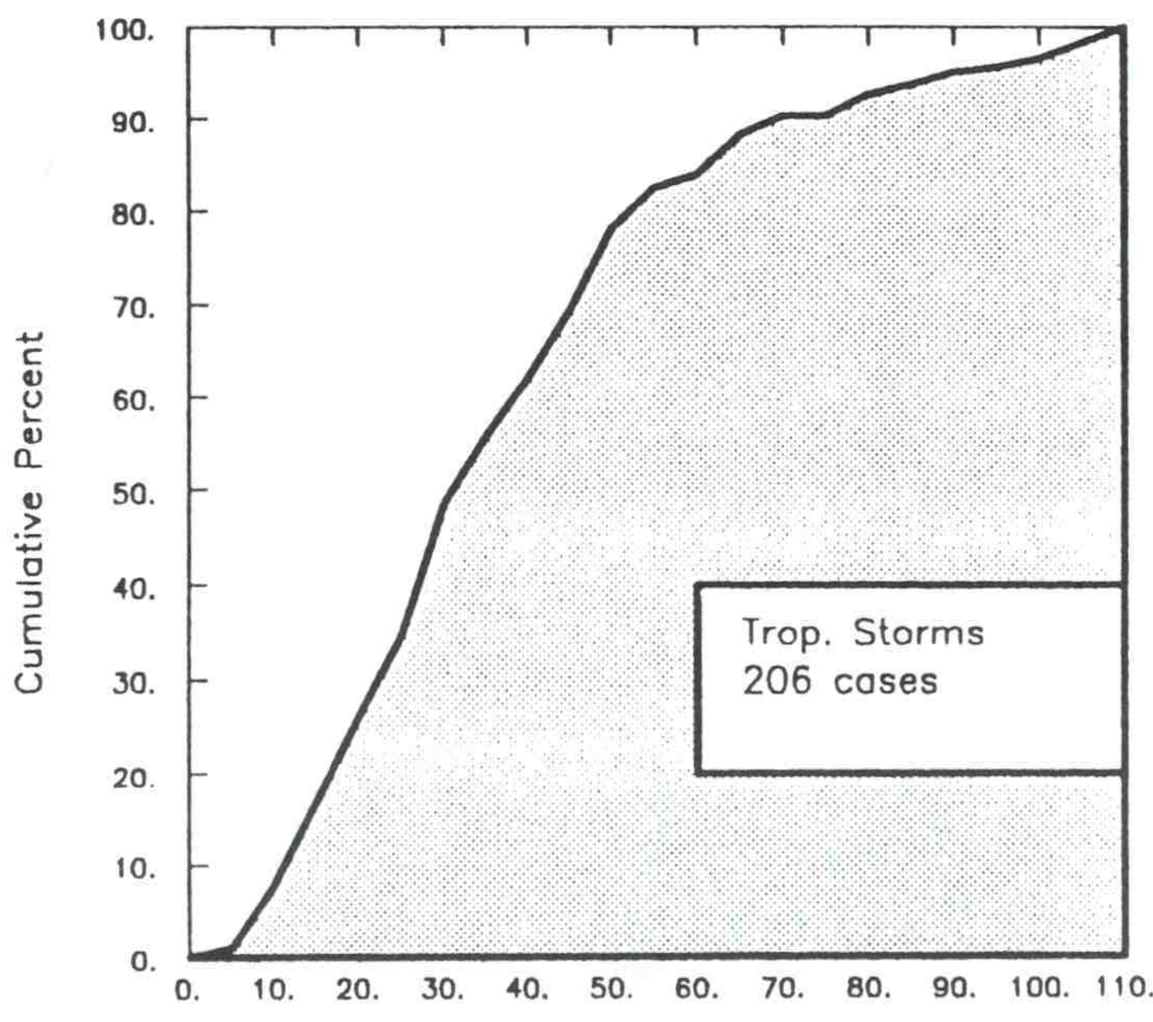


Figure 1-10. Deviations (in nmi) of AFGWC-determined positions from NHC-determined positions for tropical storms for the 1981-86 Atlantic Basin hurricane season--cumulative percentage.

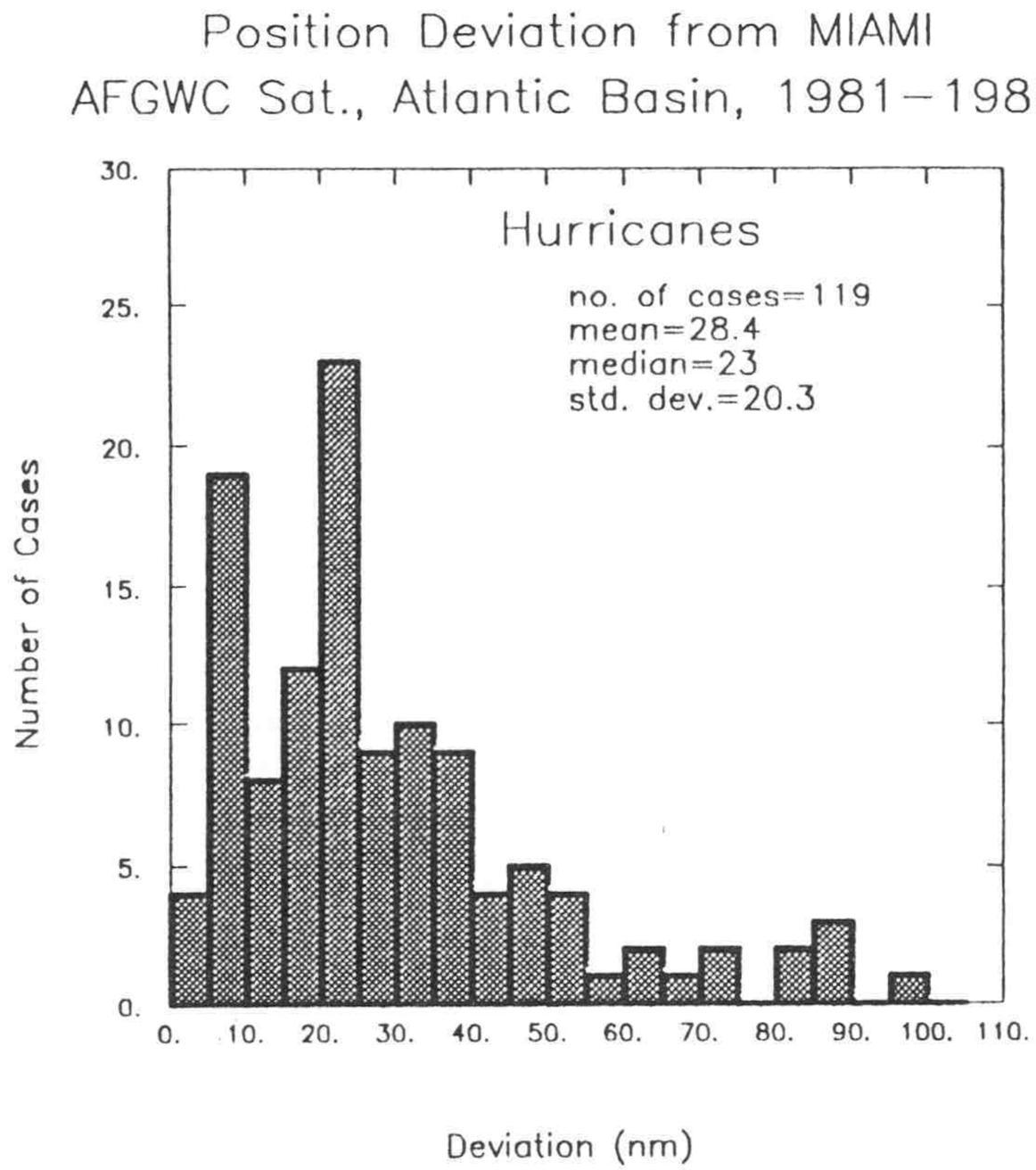


Figure 1-11. Deviations (in nmi) of AFGWC-determined positions from NHC-determined positions for hurricanes for the 1981-86 Atlantic Basin hurricane season--by number of cases.

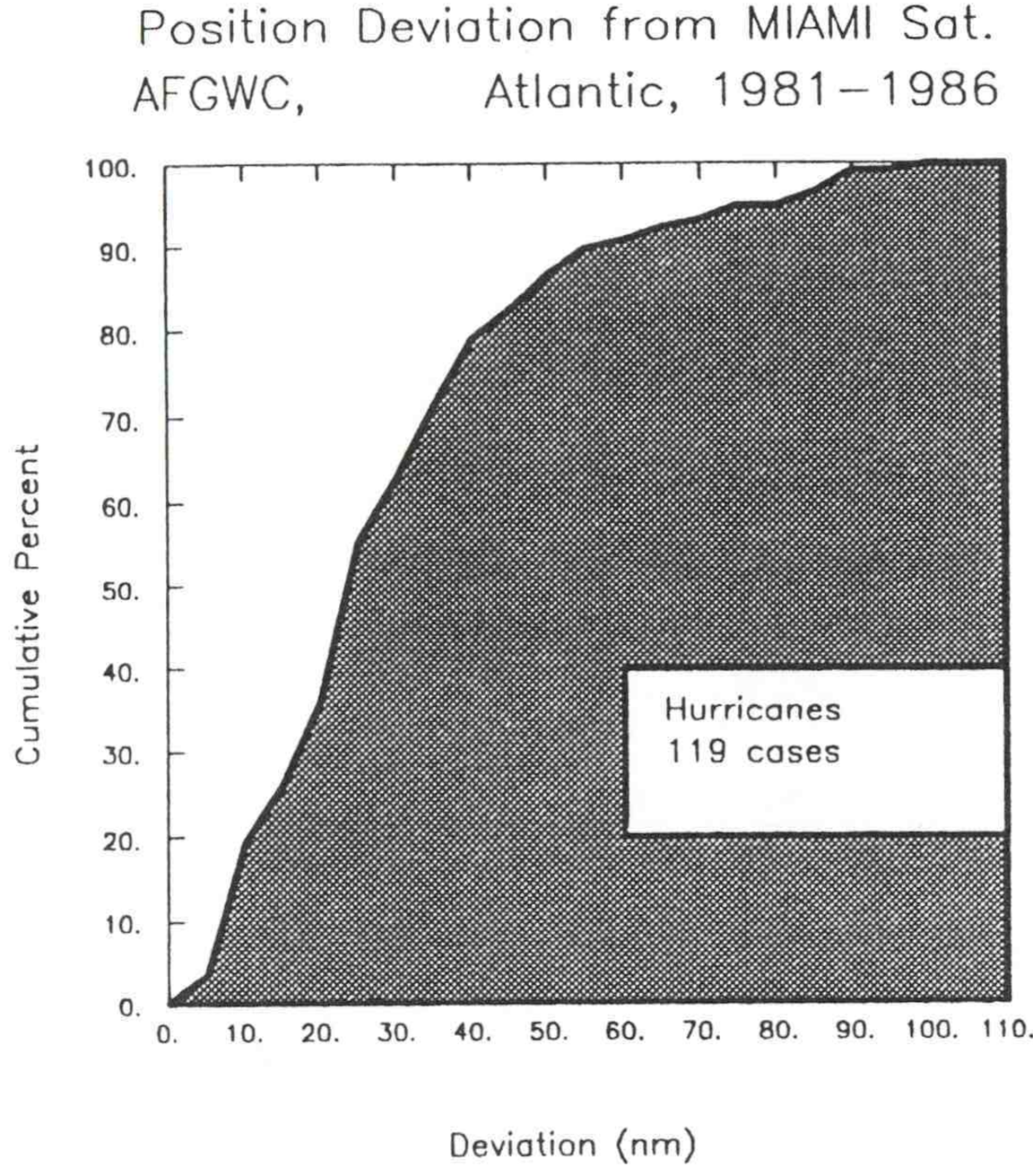


Figure 1-12. Deviations (in nmi) of AFGWC-determined positions from NHC-determined positions for hurricanes for the 1981-86 Atlantic Basin hurricane season--cumulative percentage.

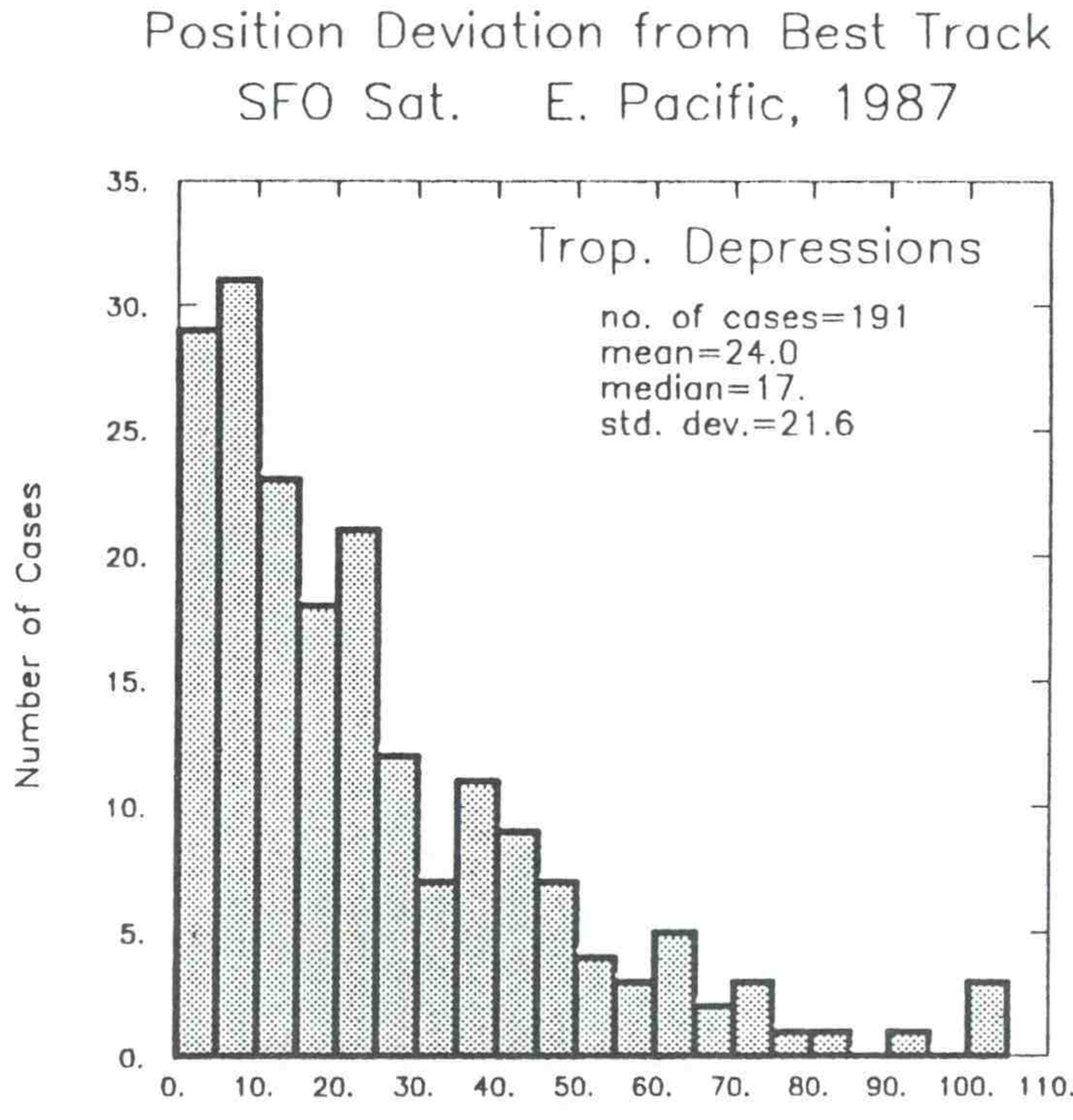


Figure 1-13. Deviations (in nmi) of EPHC-determined positions from "best track" positions for tropical depressions for the 1987 Eastern Pacific hurricane season--by number of cases.

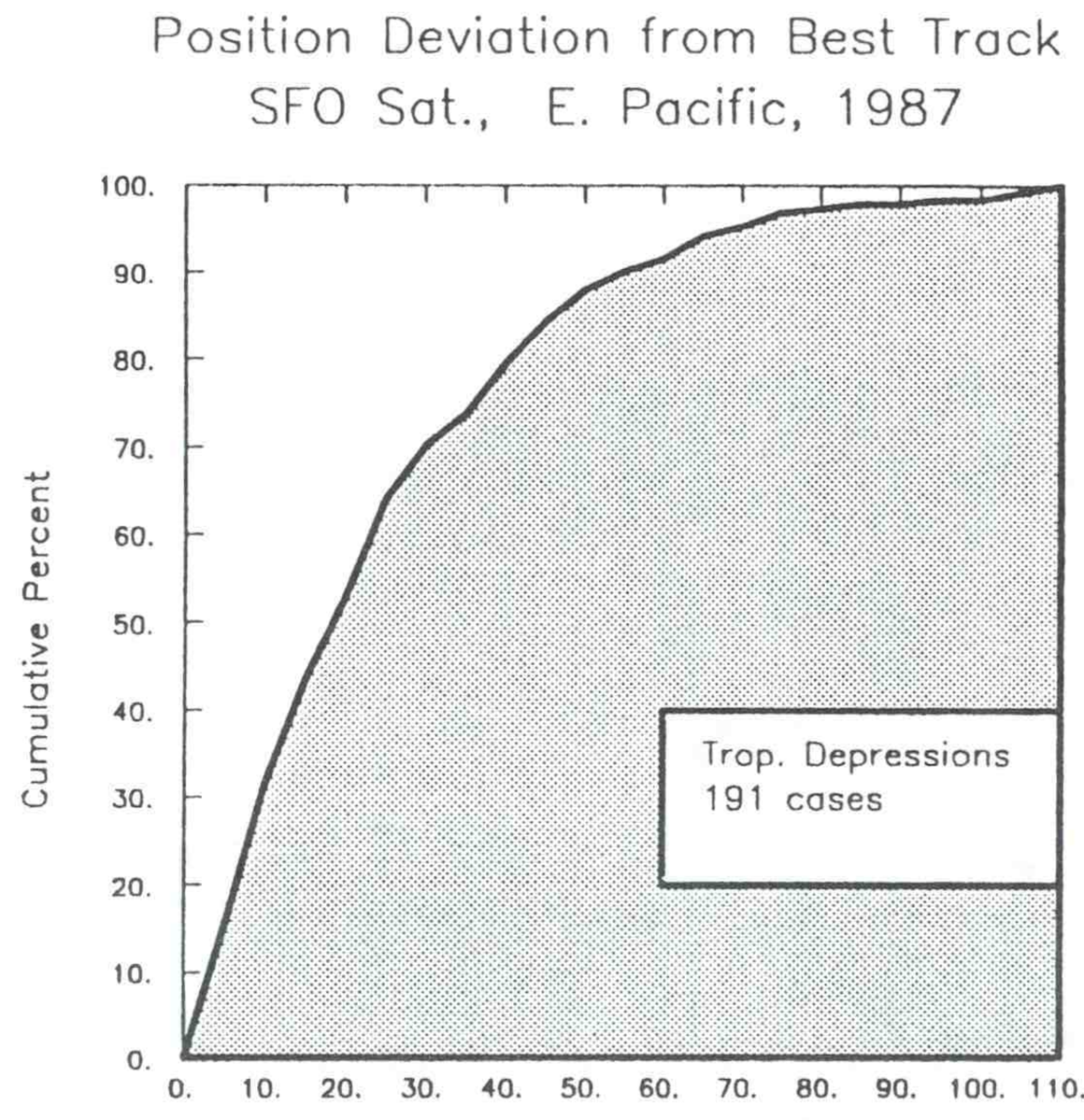


Figure 1-14. Deviations (in nmi) of EPHC-determined positions from "best track" positions for tropical depressions for the 1987 Eastern Pacific hurricane season--cumulative percentage.

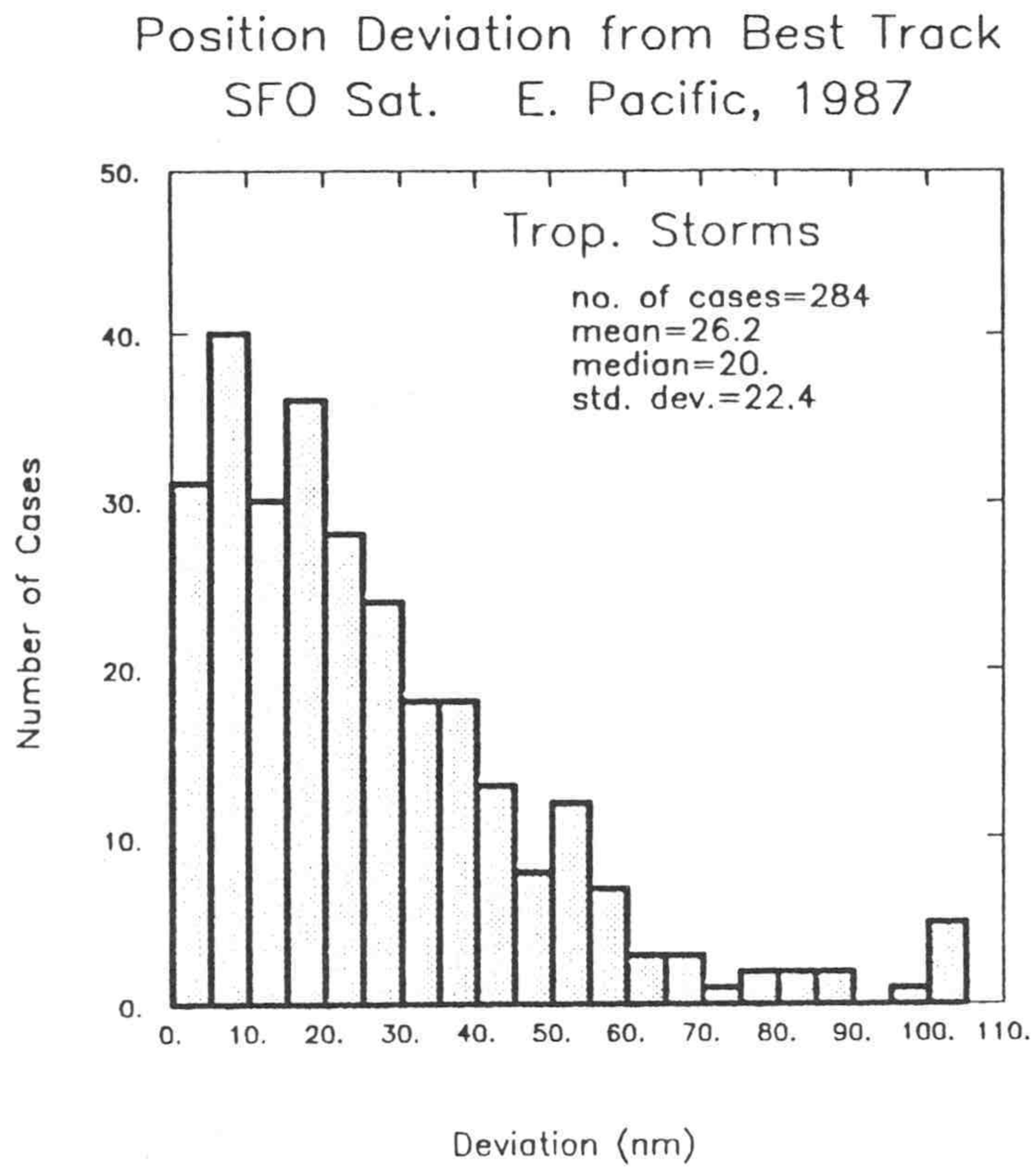


Figure 1-15. Deviations (in nmi) of EPHC-determined positions from "best track" positions for tropical storms for the 1987 Eastern Pacific hurricane season--by number of cases.

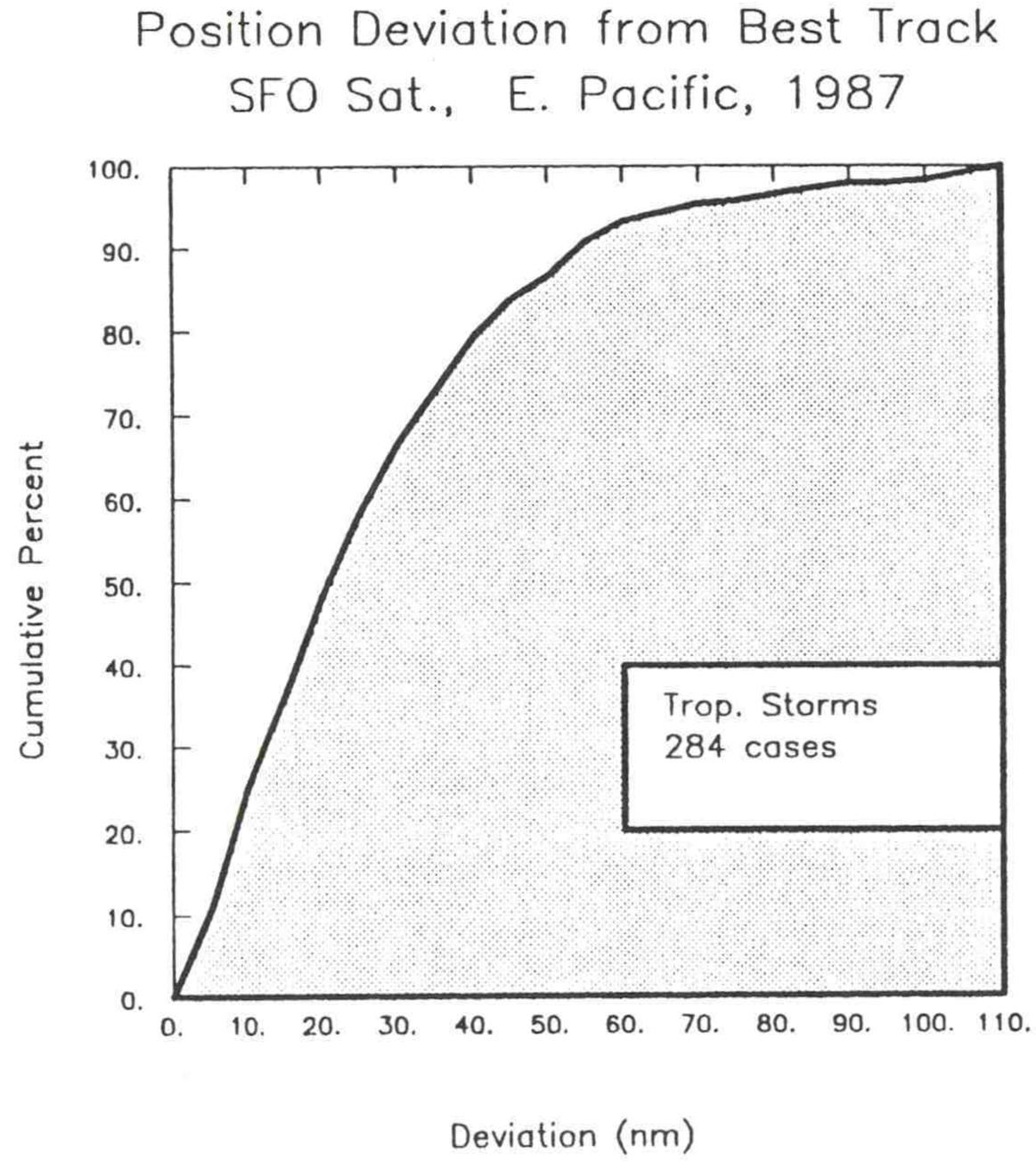


Figure 1-16. Deviations (in nmi) of EPHC-determined positions from "best track" positions for tropical storms for the 1987 Eastern Pacific hurricane season--cumulative percentage.

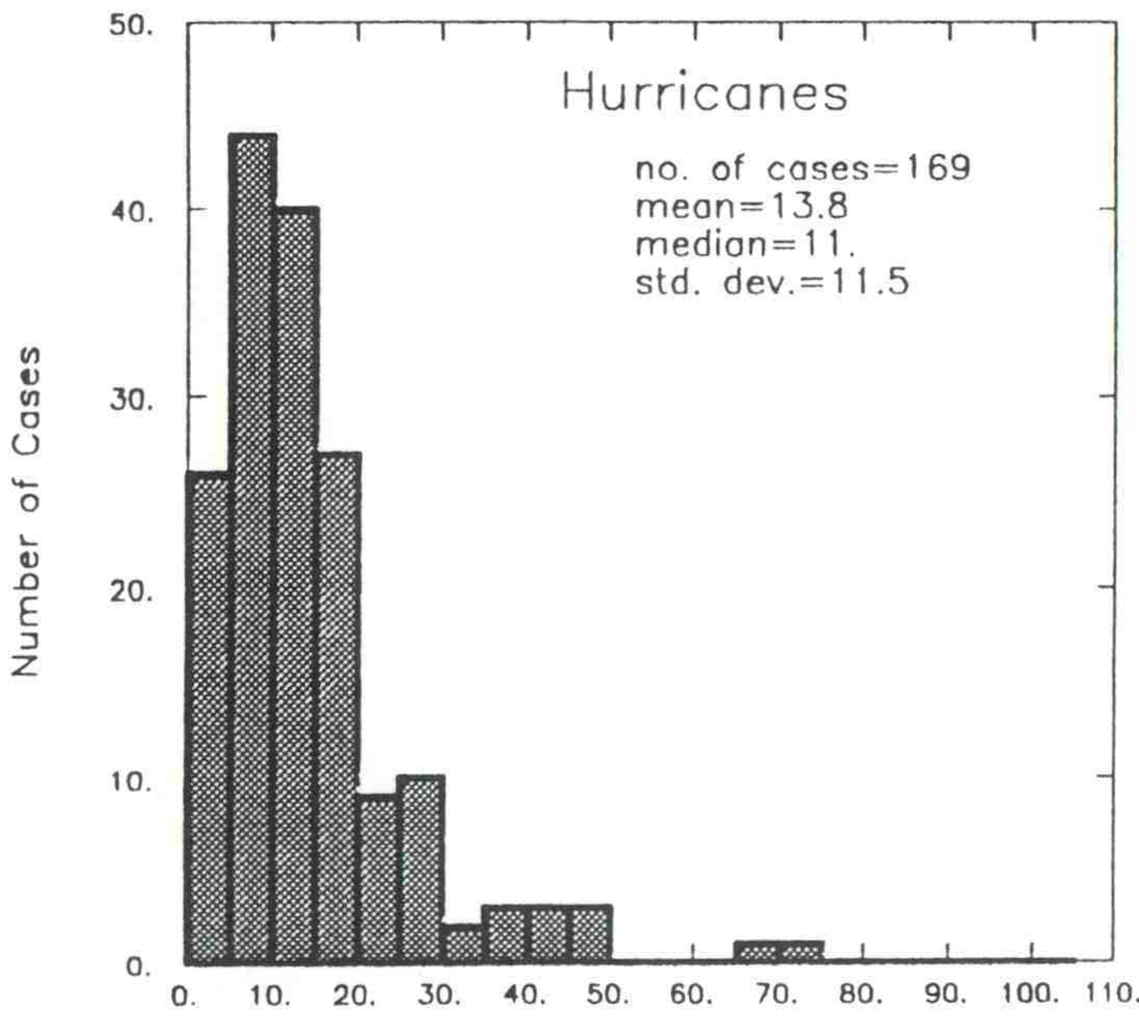


Figure 1-17. Deviations (in nmi) of EPHC-determined positions from "best track" positions for hurricanes for the 1987 Eastern Pacific hurricane season--by number of cases.

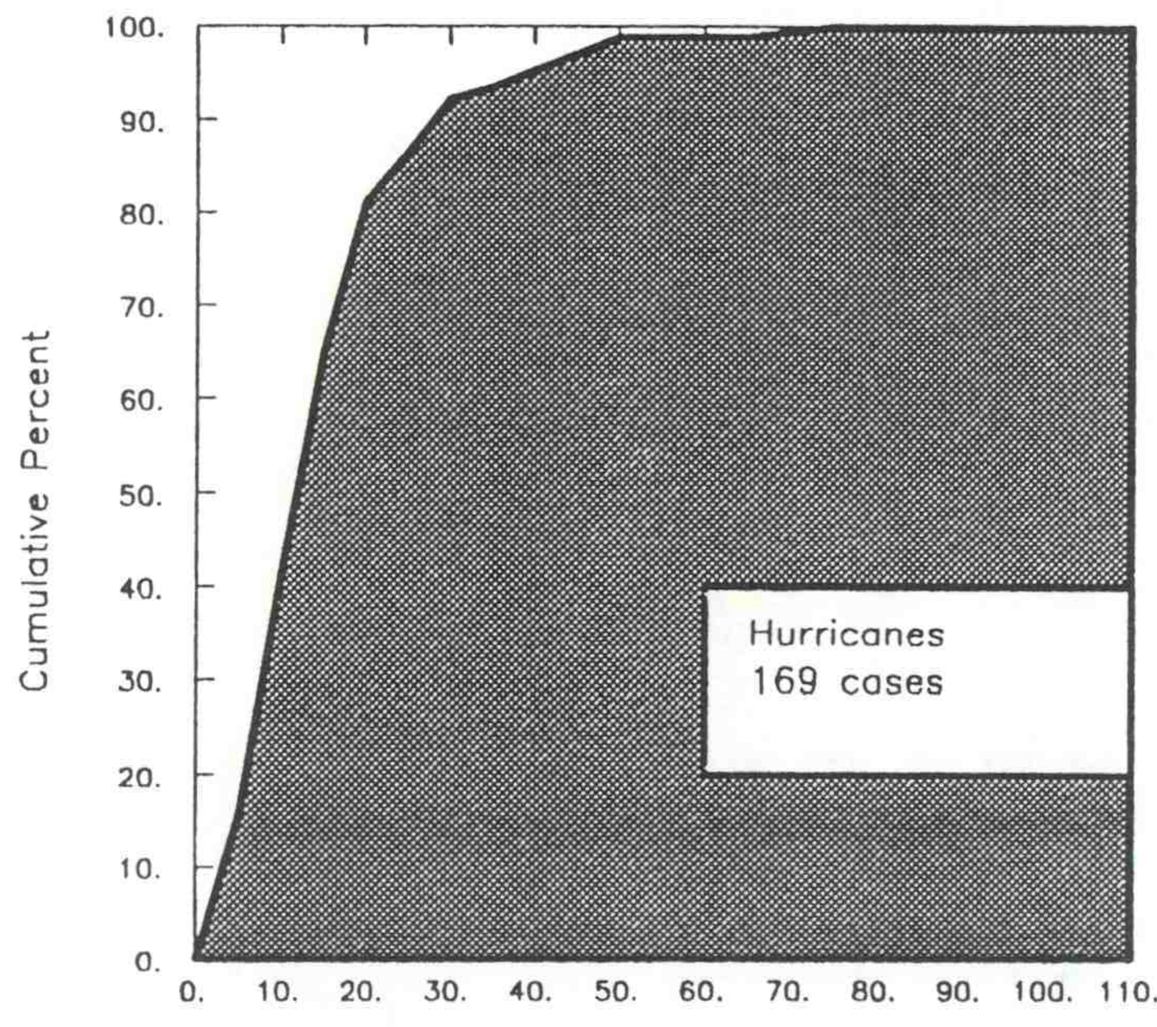


Figure 1-18. Deviations (in nmi) of EPHC-determined positions from "best track" positions for hurricanes for the 1987 Eastern Pacific hurricane season--cumulative percentage.

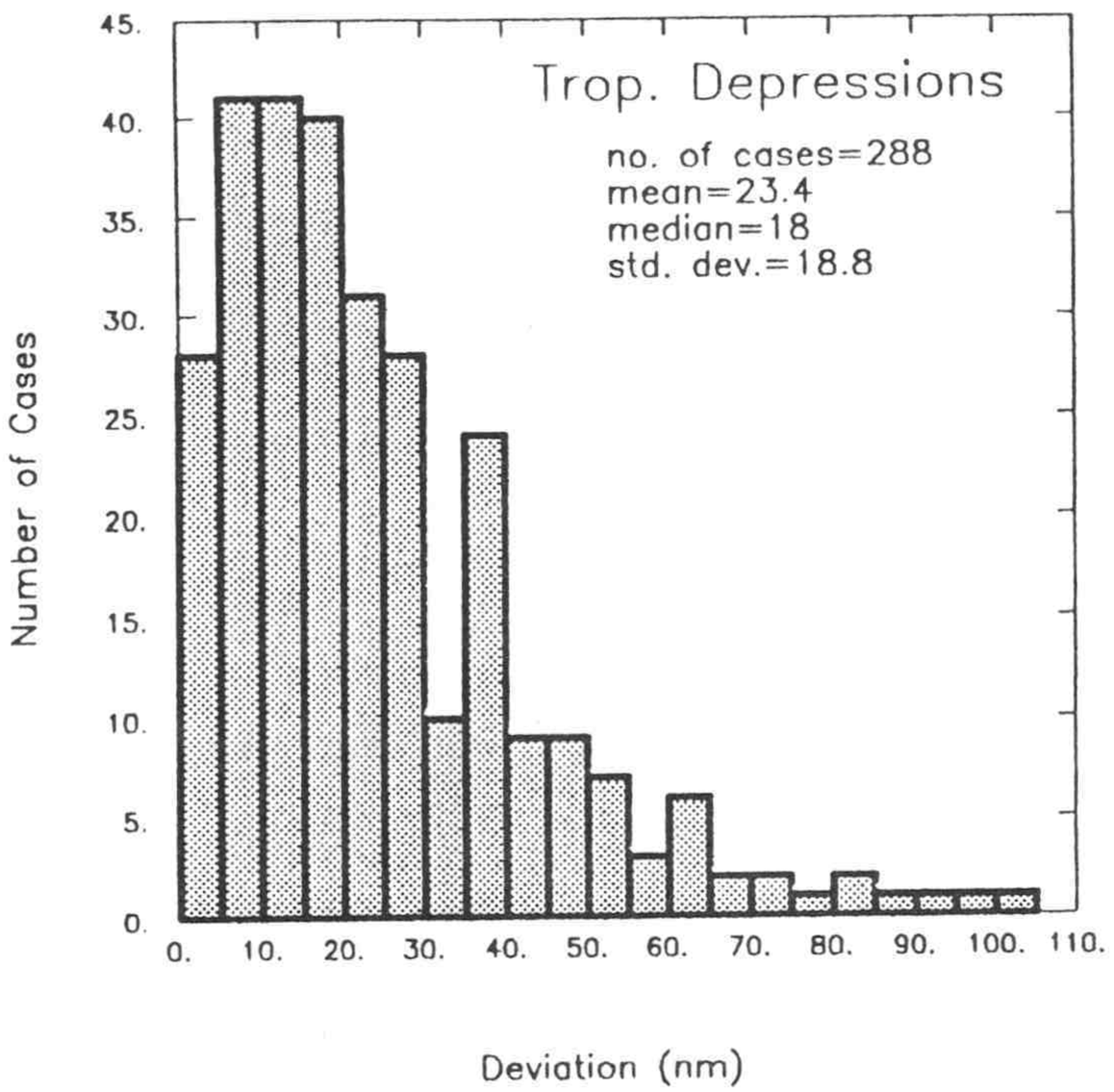


Figure 1-19. Deviations (in nmi) of NHC-determined positions from "best track" positions for tropical depressions for the 1981-86 Atlantic Basin hurricane season--by number of cases.

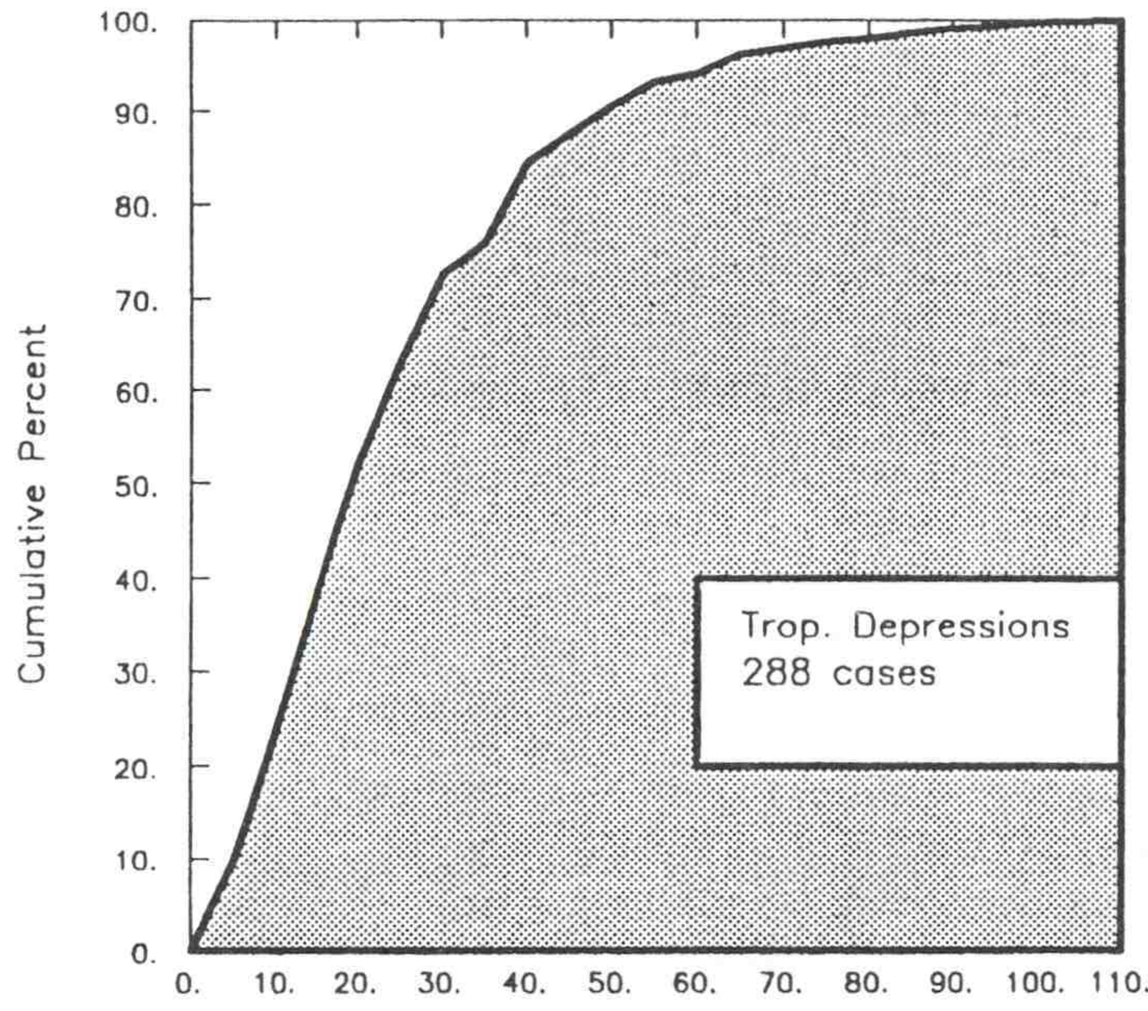


Figure 1-20. Deviations (in nmi) of NHC-determined positions from "best track" positions for tropical depressions for the 1981-86 Atlantic Basin hurricane season--cumulative percentage.

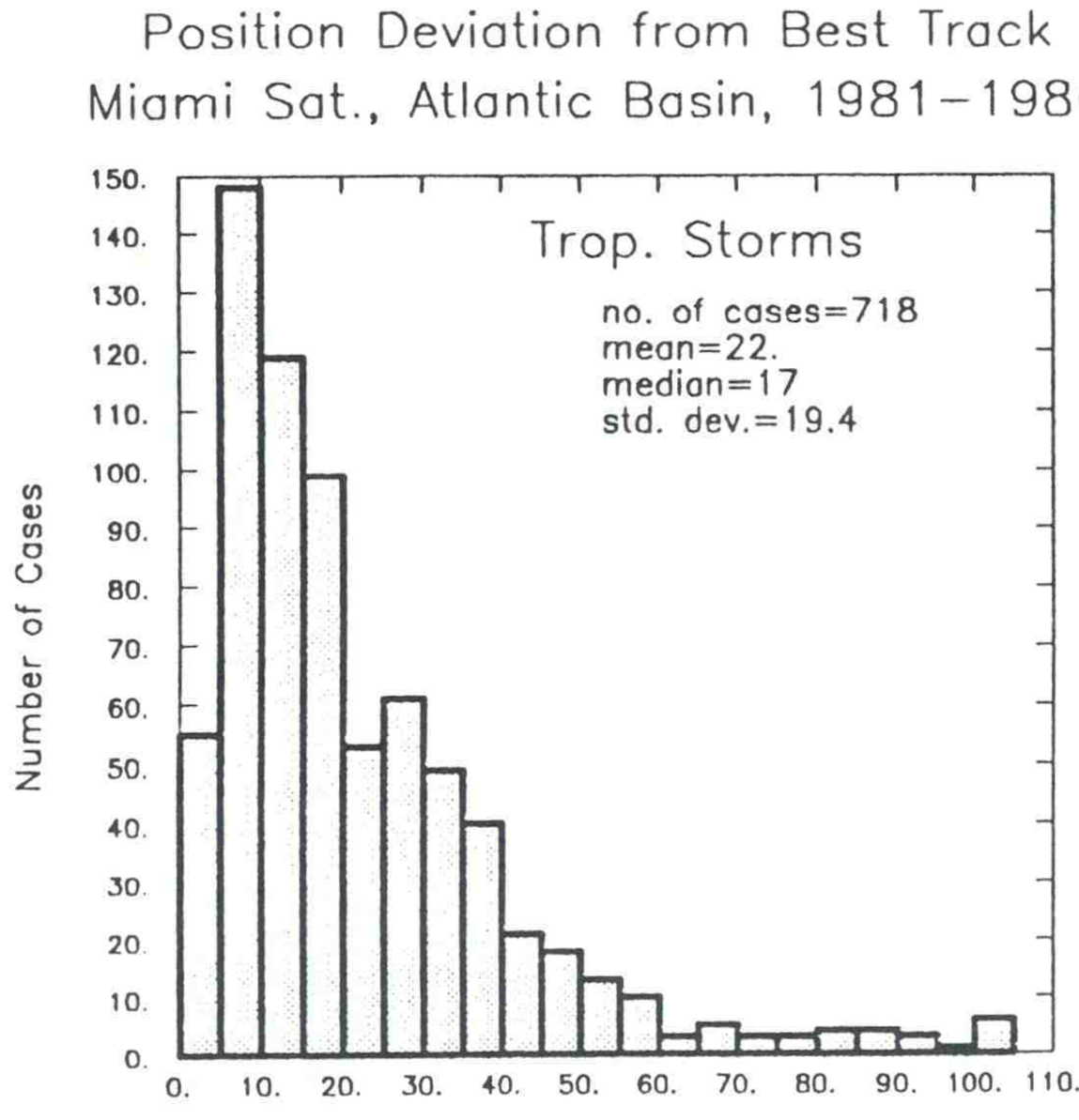


Figure 1-21. Deviations (in nmi) of NHC-determined positions from "best track" positions for tropical storms for the 1981-86 Atlantic Basin hurricane season--by number of cases.

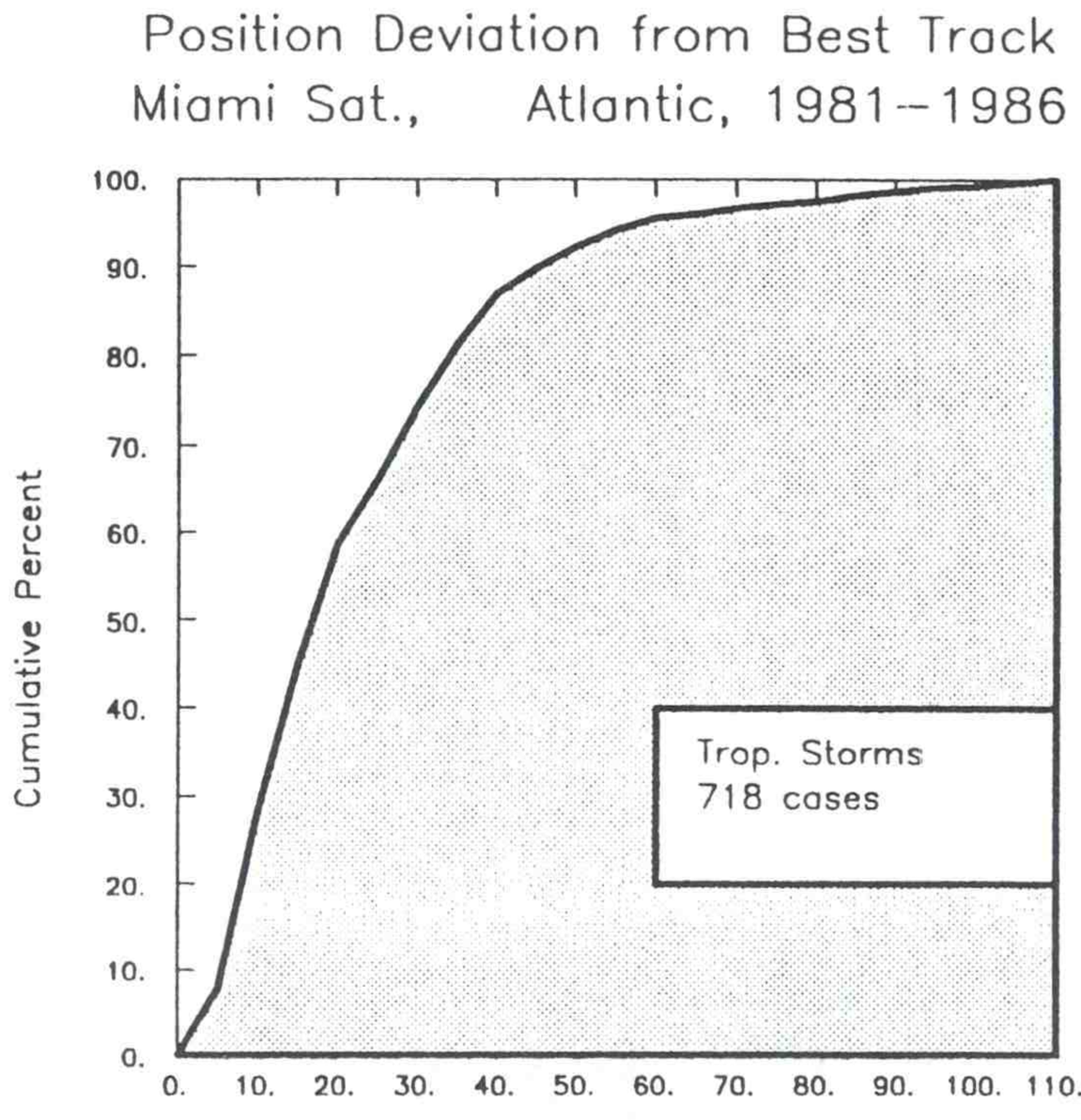


Figure 1-22. Deviations (in nmi) of NHC-determined positions from "best track" positions for tropical storms for the 1981-86 Atlantic Basin hurricane season--cumulative percentage.

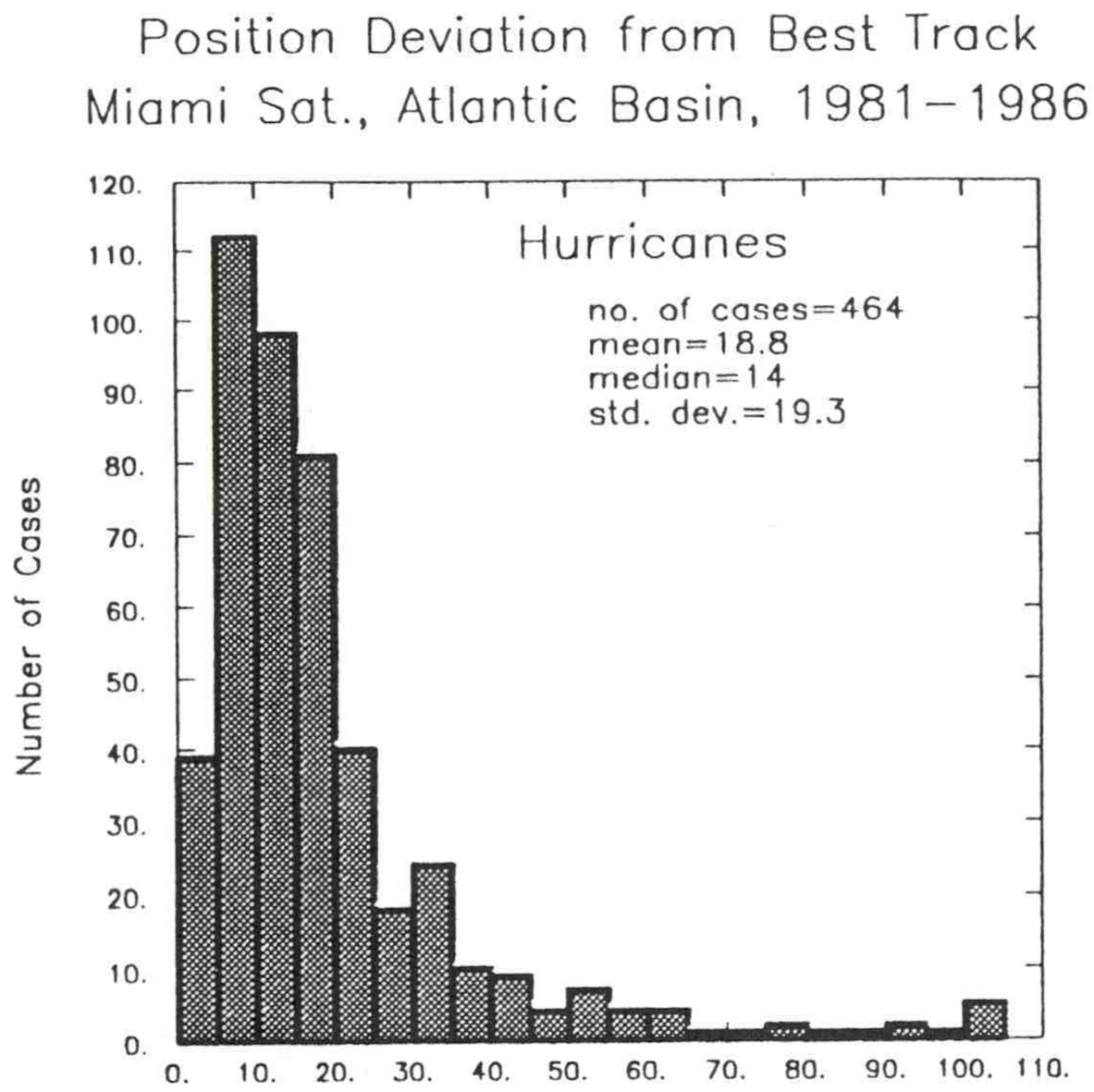


Figure 1-23. Deviations (in nmi) of NHC-determined positions from "best track" positions for hurricanes for the 1981-86 Atlantic Basin hurricane season--by number of cases.

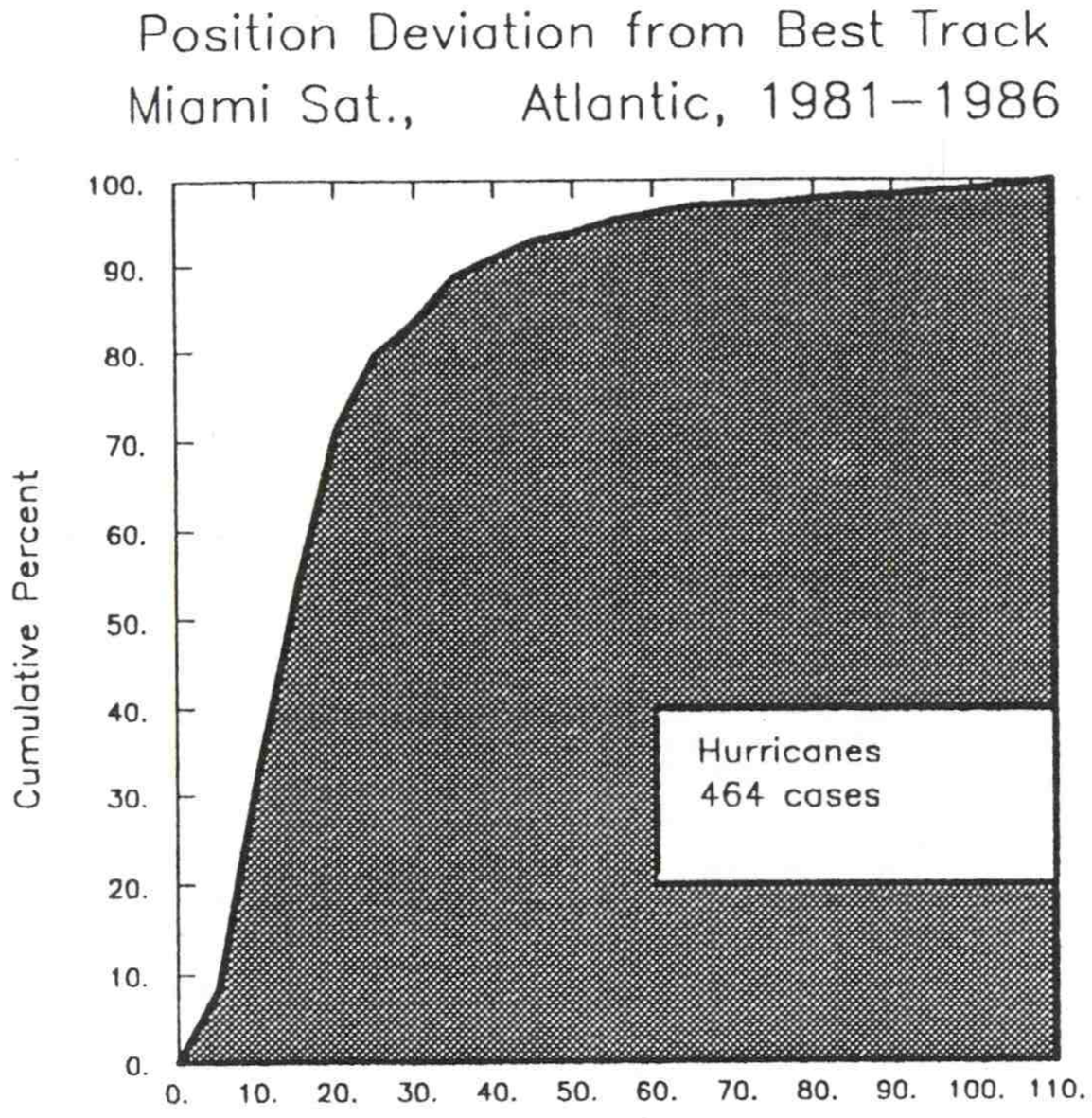


Figure 1-24. Deviations (in nmi) of NHC-determined positions from "best track" positions for hurricanes for the 1981-86 Atlantic Basin hurricane season--cumulative percentage.

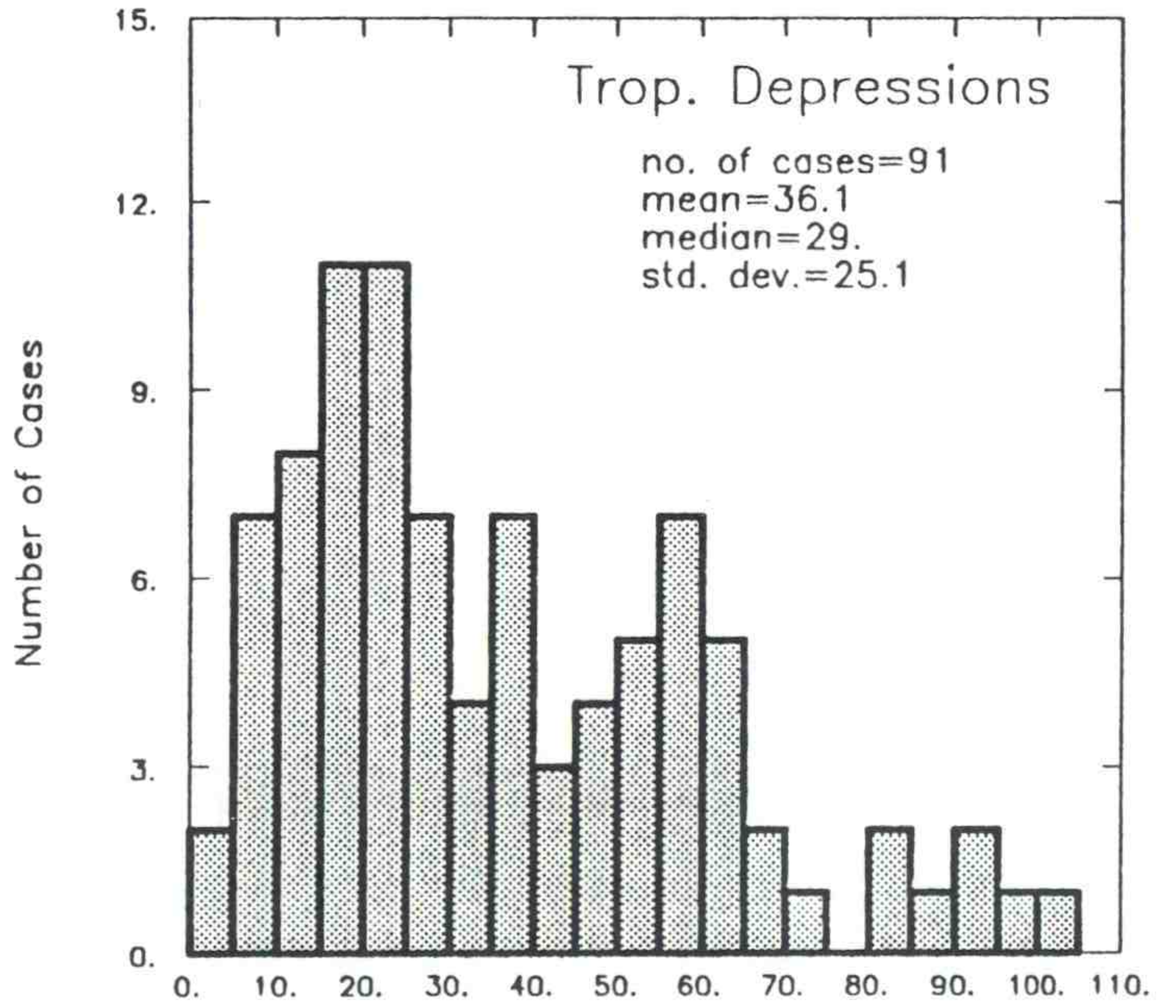


Figure 1-25. Deviations (in nmi) of AFGWC-determined positions from "best track" positions for tropical depressions for the 1981-86 Atlantic Basin hurricane season--by number of cases.

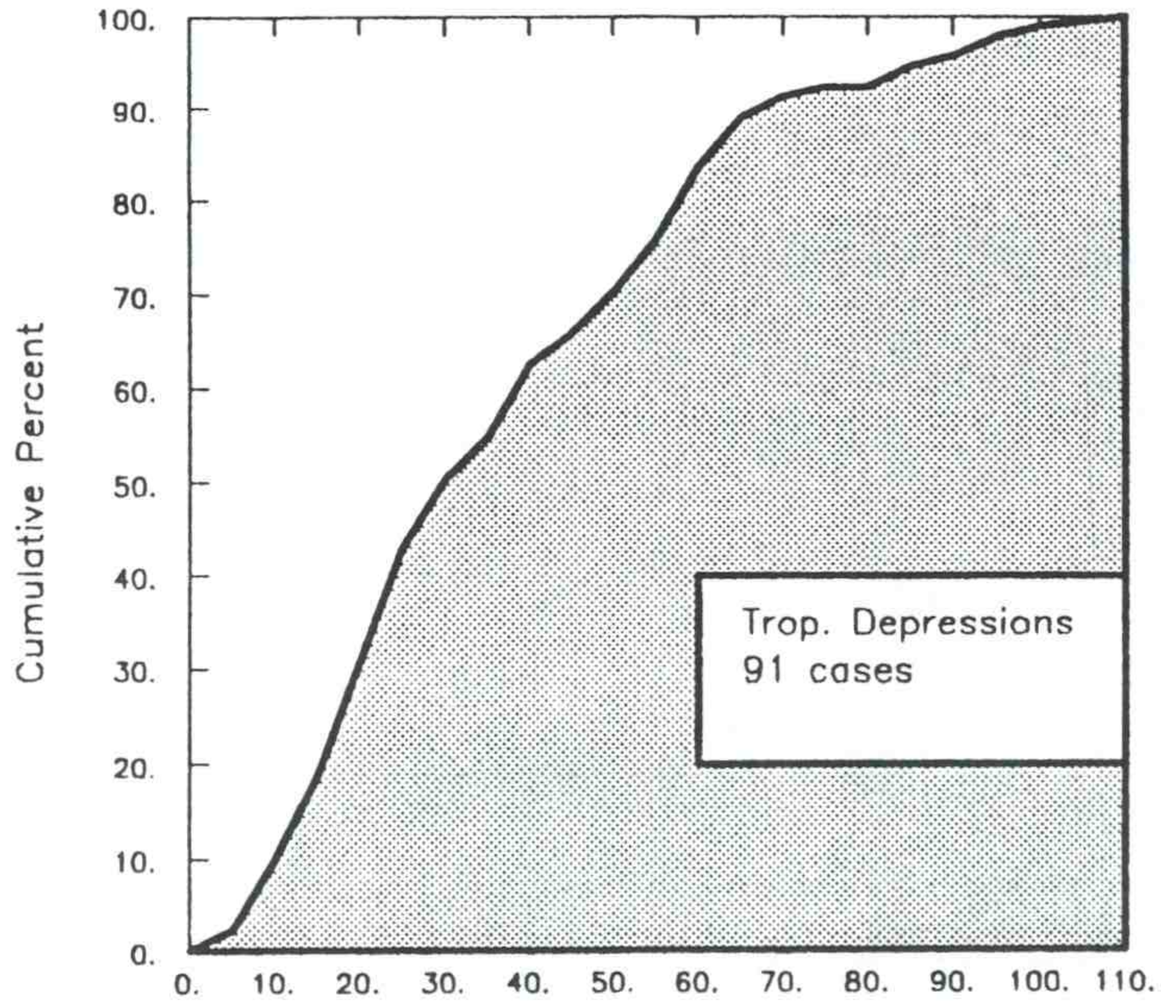


Figure 1-26. Deviations (in nmi) of AFGWC-determined positions from "best track" positions for tropical depressions for the 1981-86 Atlantic Basin hurricane season--cumulative percentage.

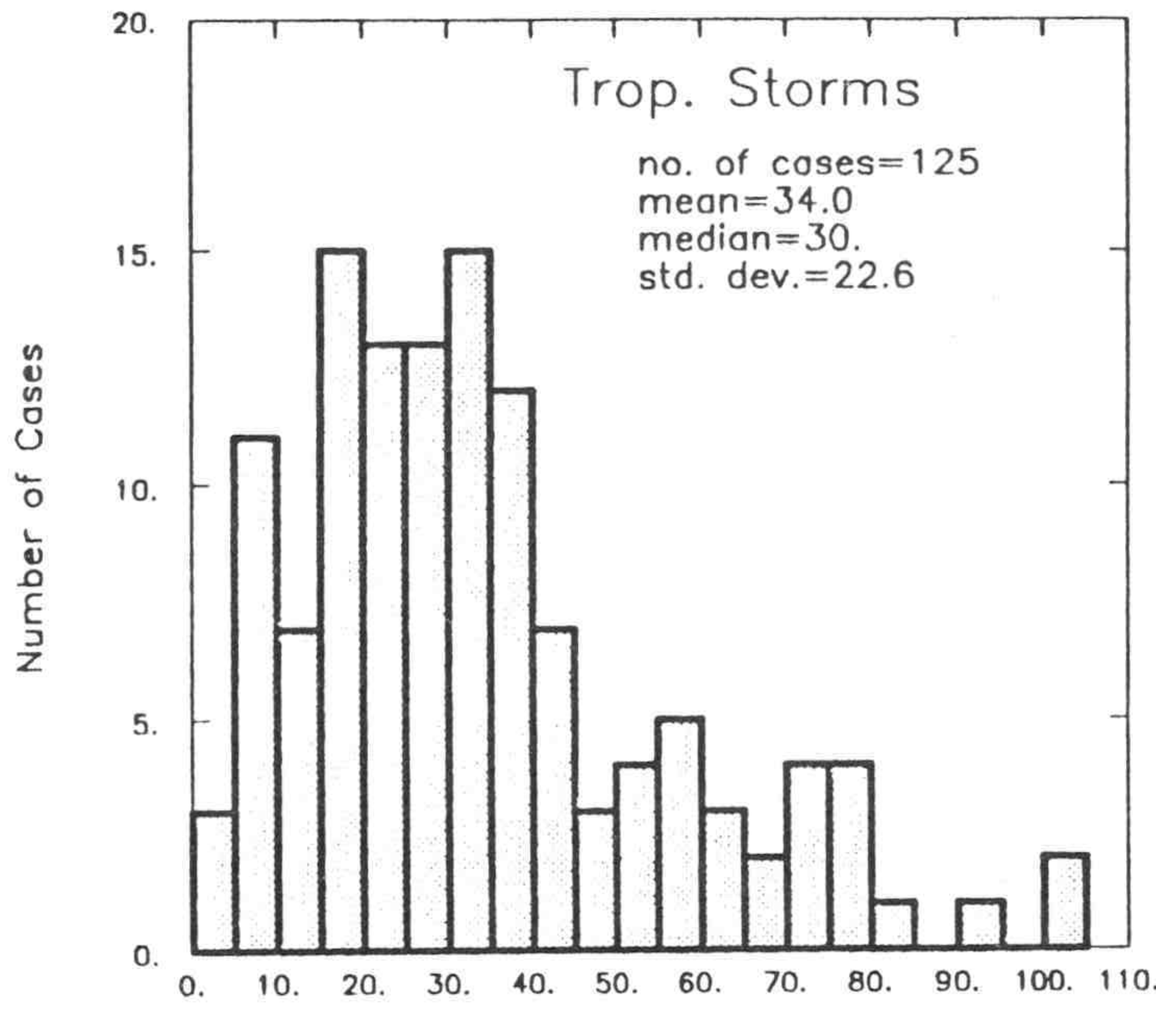


Figure 1-27. Deviations (in nmi) of AFGWC-determined positions from "best track" positions for tropical storms for the 1981-86 Atlantic Basin hurricane season--by number of cases.

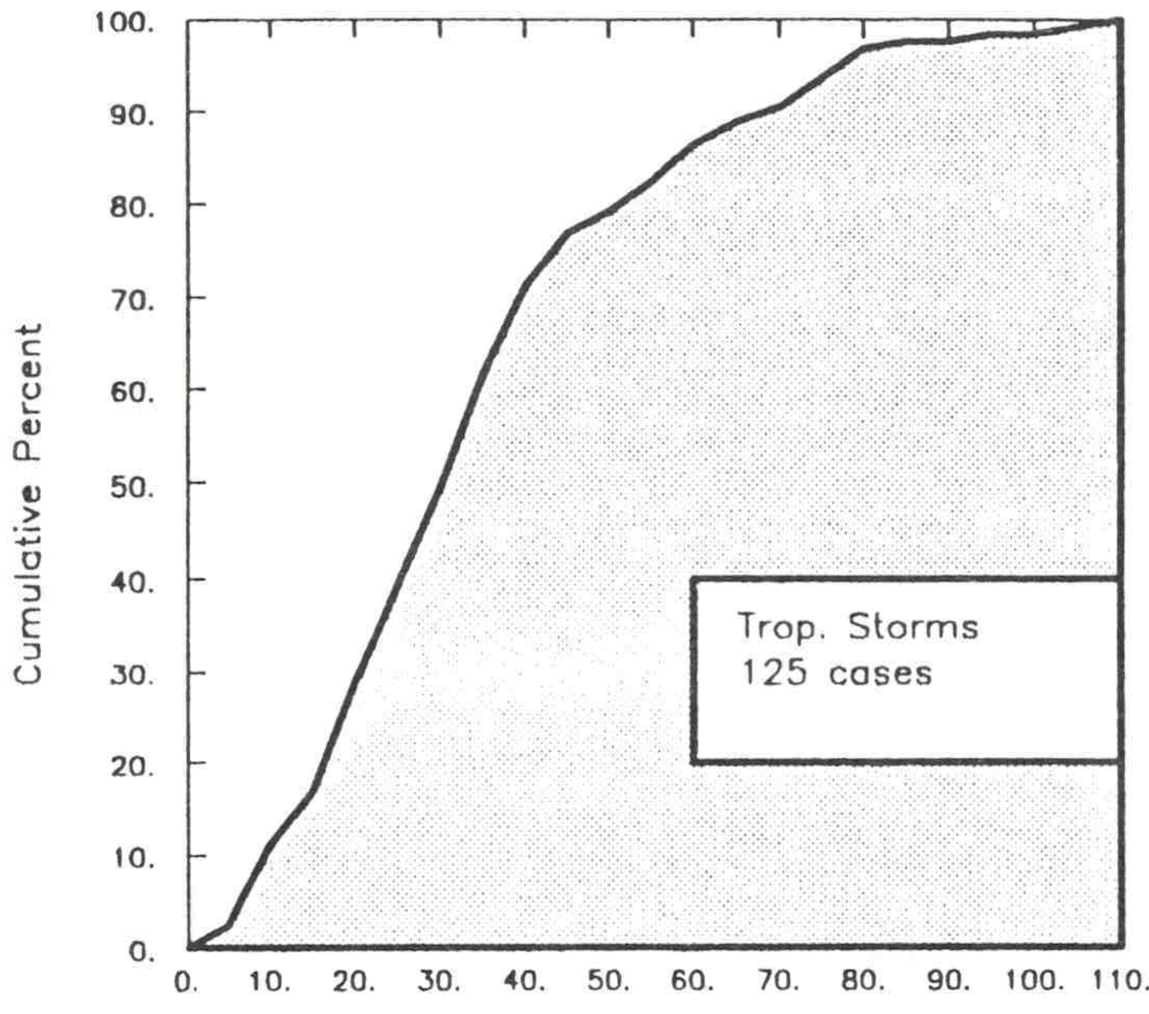


Figure 1-28. Deviations (in nmi) of AFGWC-determined positions from "best track" positions for tropical storms for the 1981-86 Atlantic Basin hurricane season--cumulative percentage.

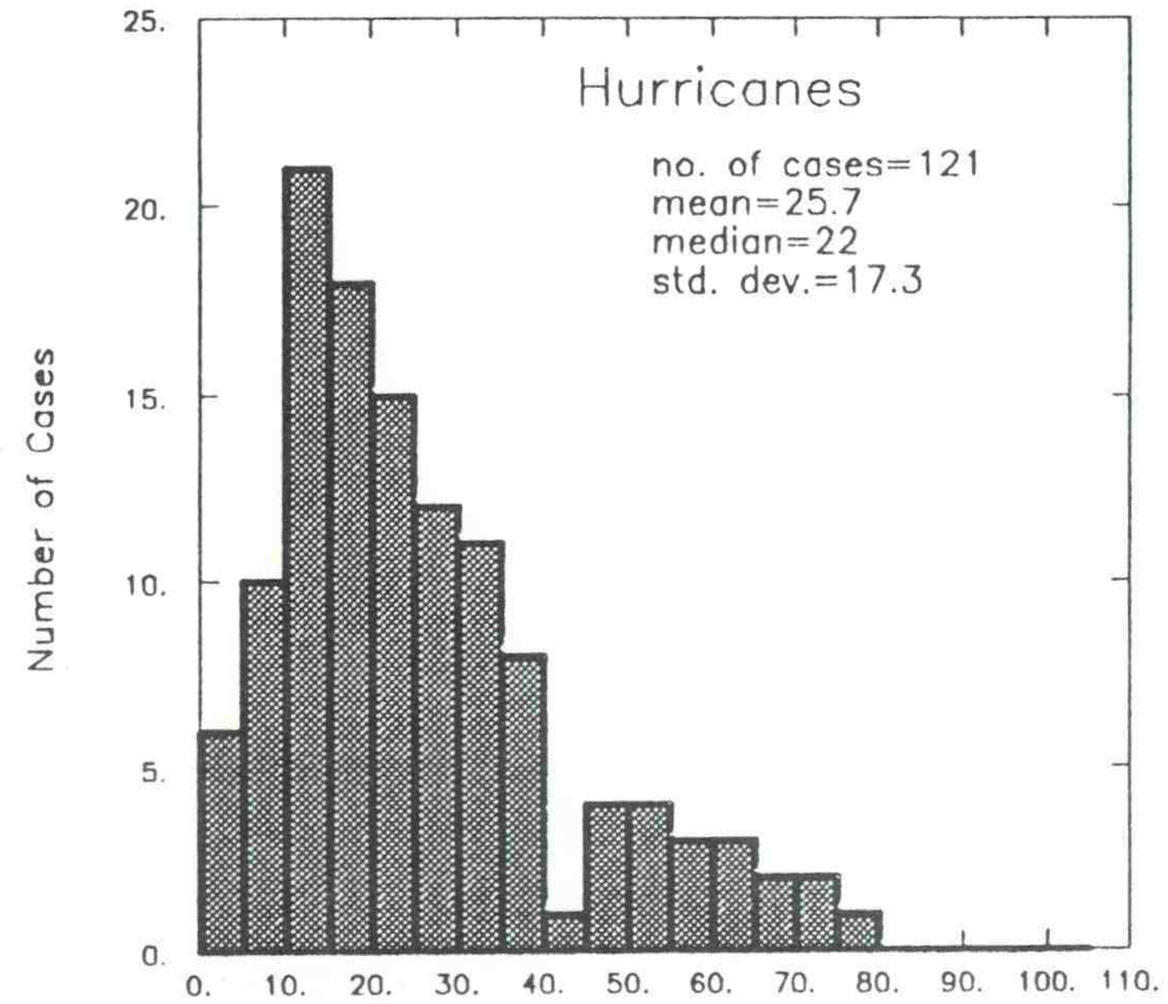


Figure 1-29. Deviations (in nmi) of AFGWC-determined positions from "best track" positions for hurricanes for the 1981-86 Atlantic Basin hurricane season--by number of cases.

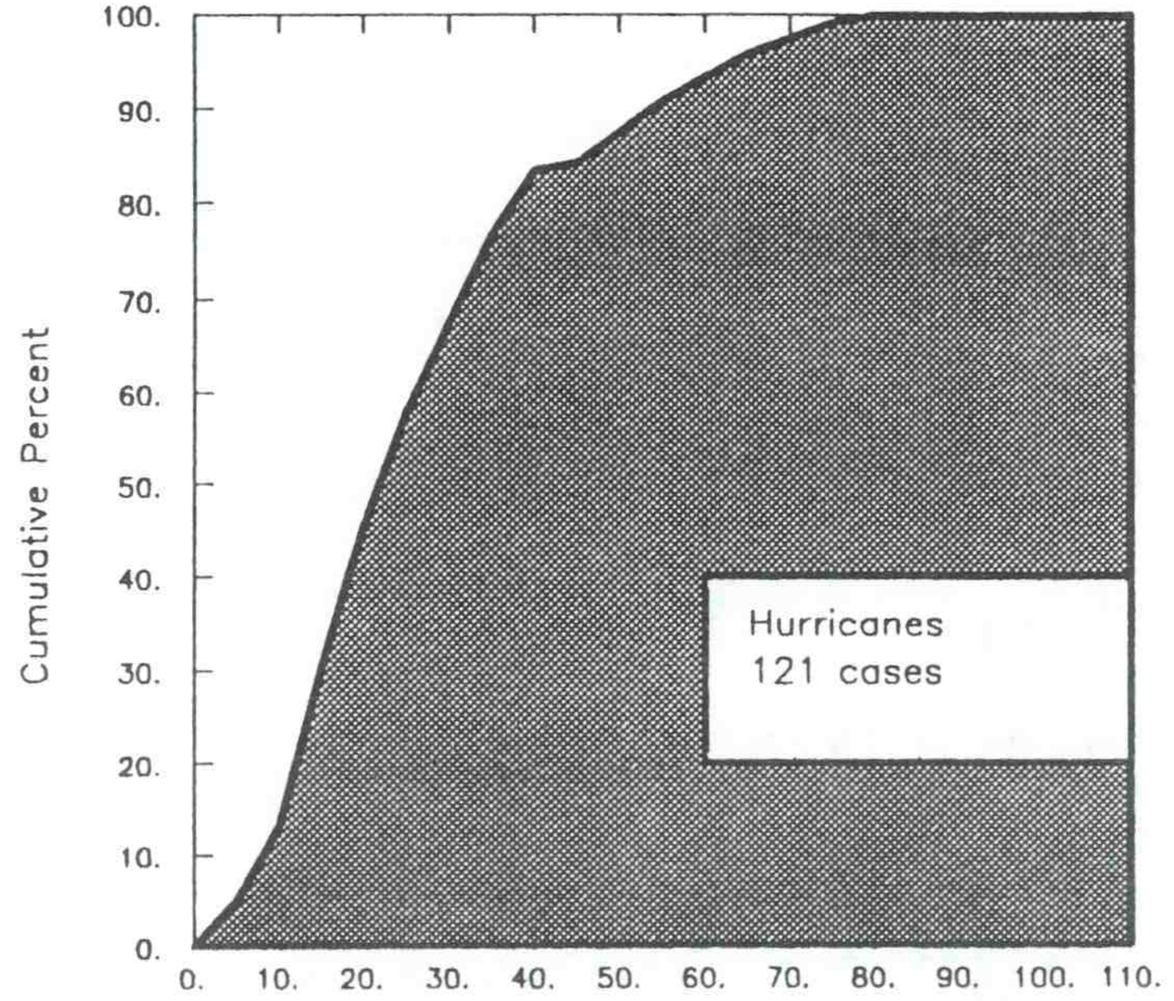


Figure 1-30. Deviations (in nmi) of AFGWC-determined positions from "best track" positions for hurricanes for the 1981-86 Atlantic Basin hurricane season--cumulative percentage.

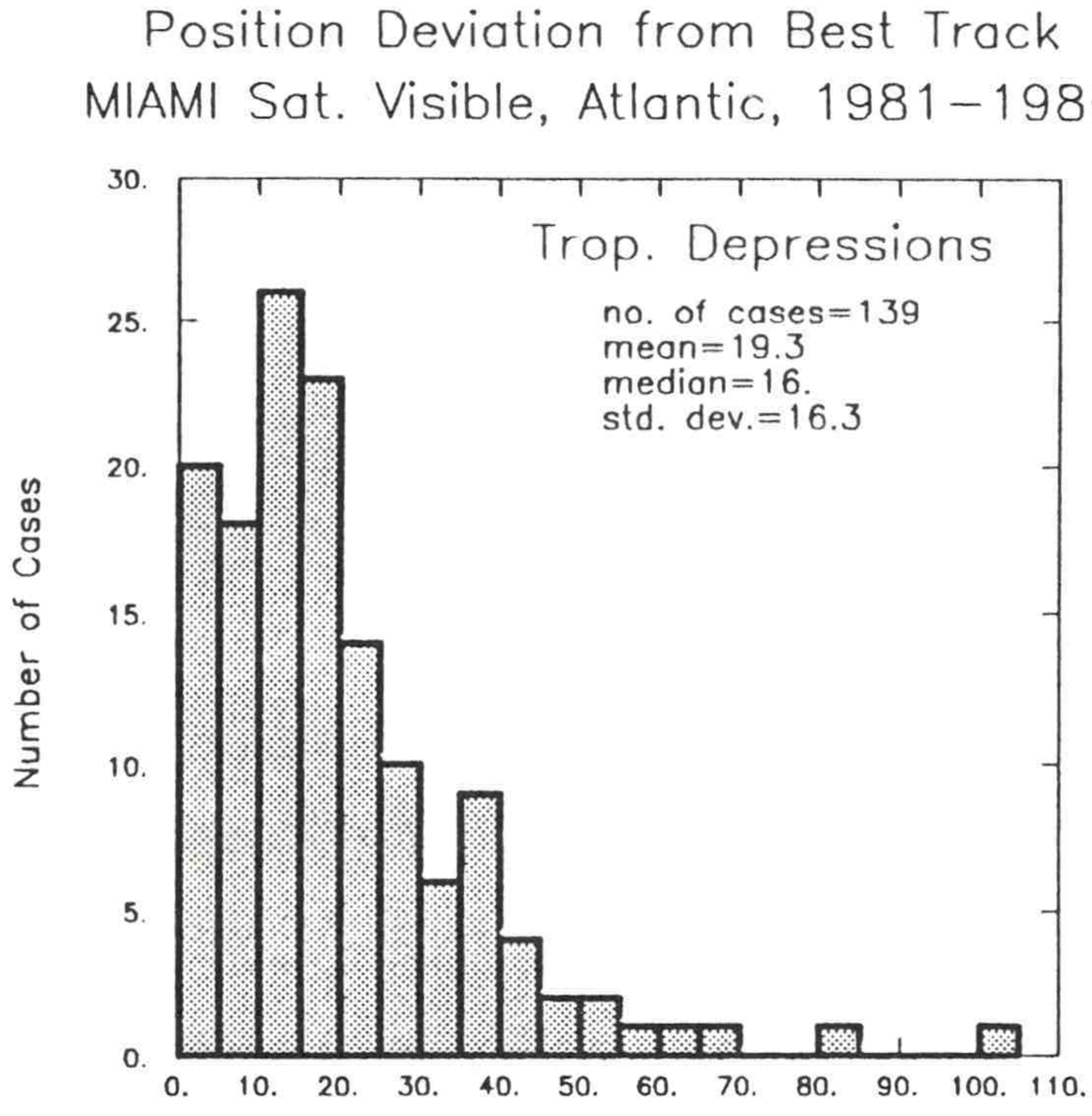


Figure 1-31. Deviations (in nmi) of NHC-determined positions from "best track" positions using visible spectra data for tropical depressions for the 1981-86 Atlantic Basin hurricane season--by number of cases.

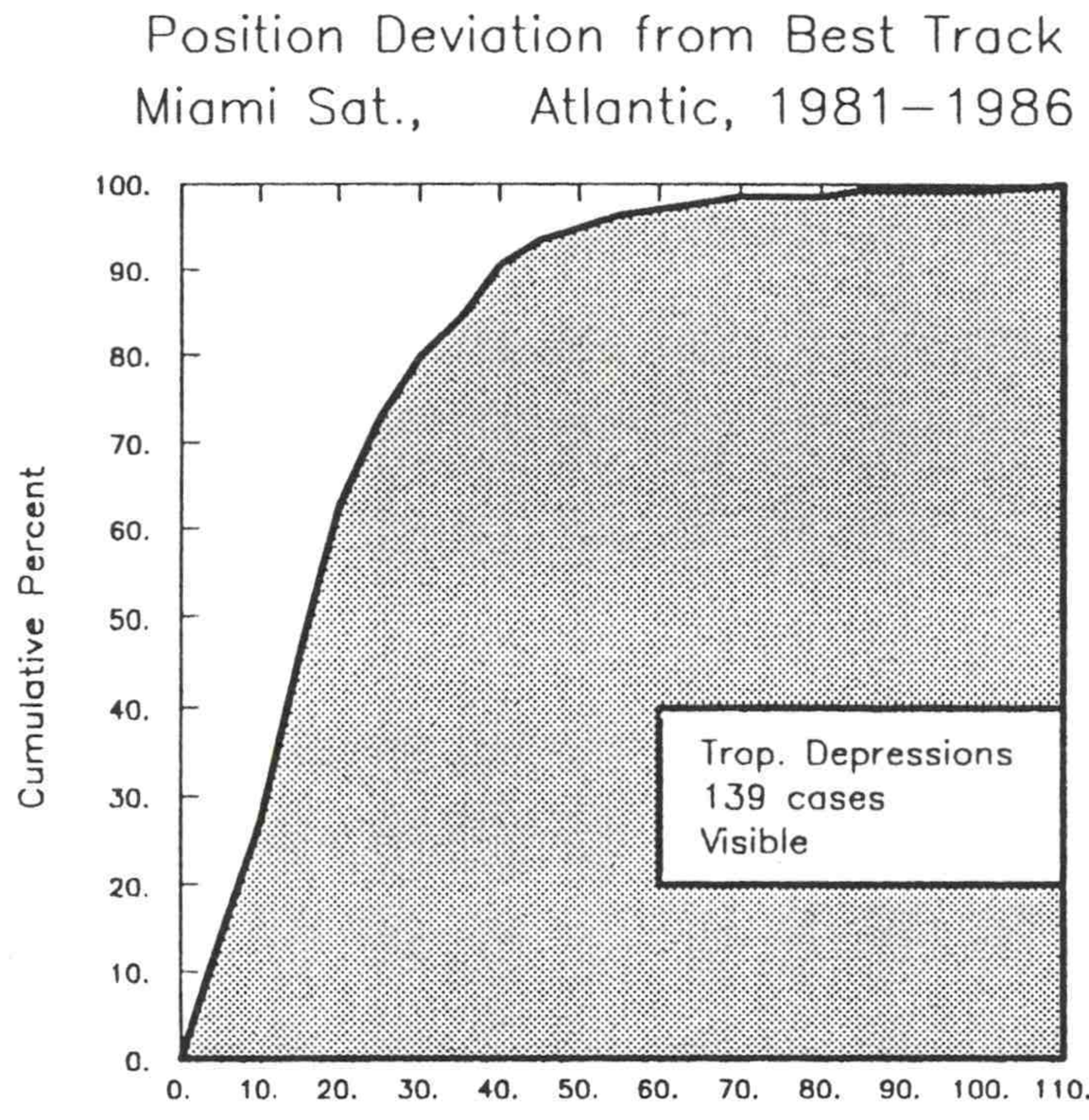


Figure 1-32. Deviations (in nmi) of NHC-determined positions from "best track" positions using visible spectra data for tropical depressions for the 1981-86 Atlantic Basin hurricane season--cumulative percentage.

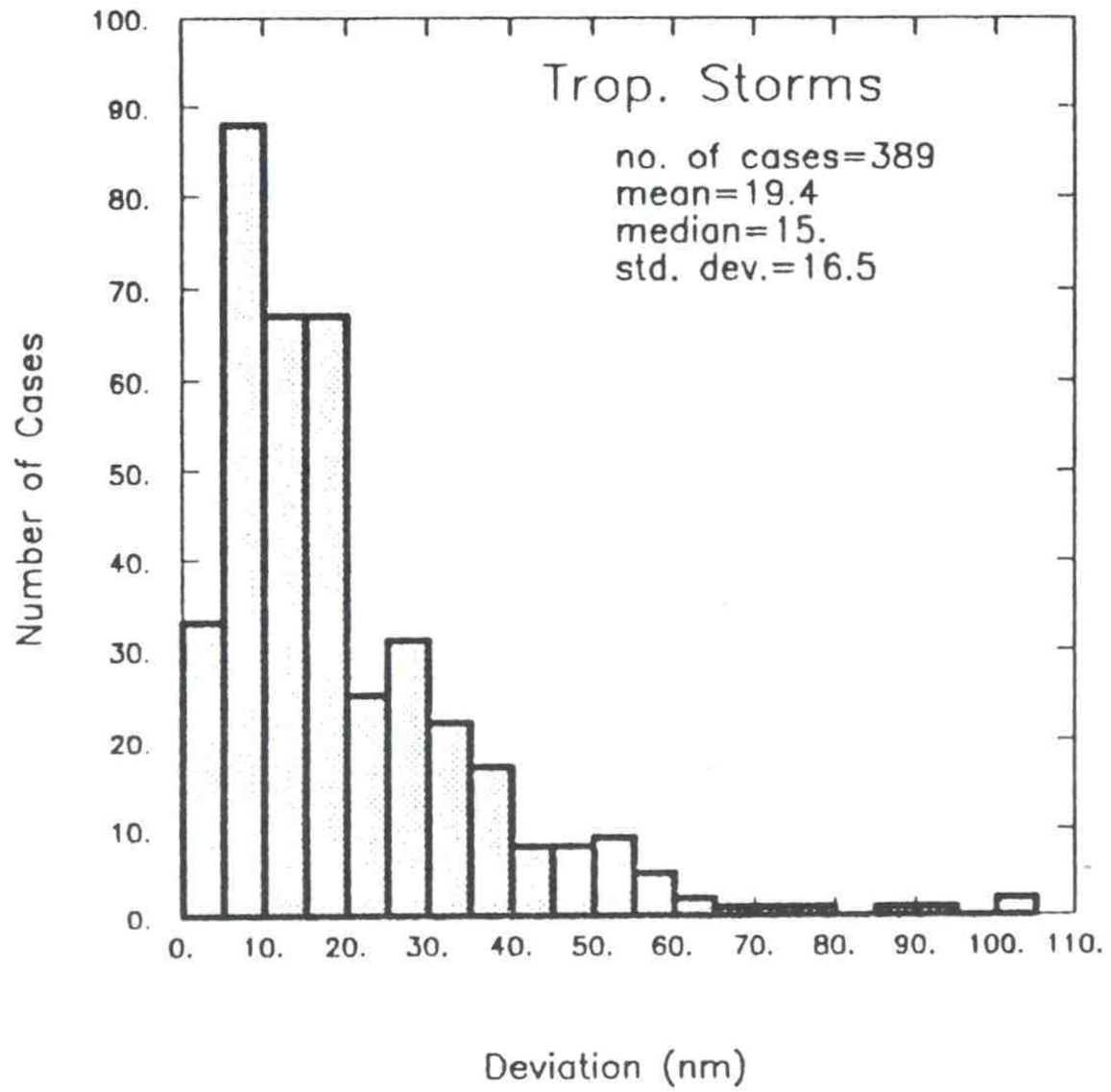


Figure 1-33. Deviations (in nmi) of NHC-determined positions from "best track" positions using visible spectra data or tropical storms for the 1981-86 Atlantic Basin hurricane season--by number of cases.

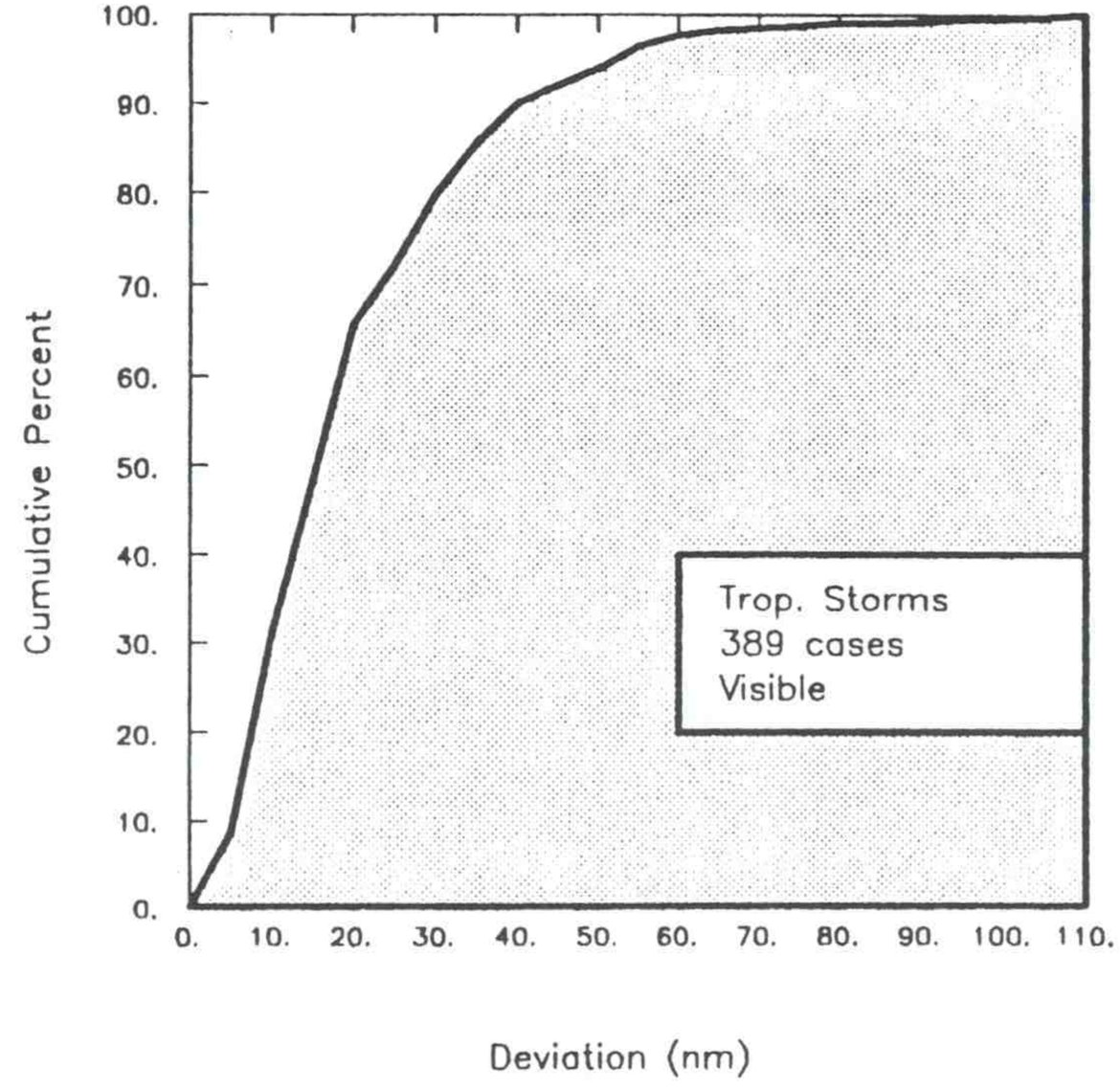


Figure 1-34. Deviations (in nmi) of NHC-determined positions from "best track" positions using visible spectra data for tropical storms for the 1981-86 Atlantic Basin hurricane season--cumulative percentage.

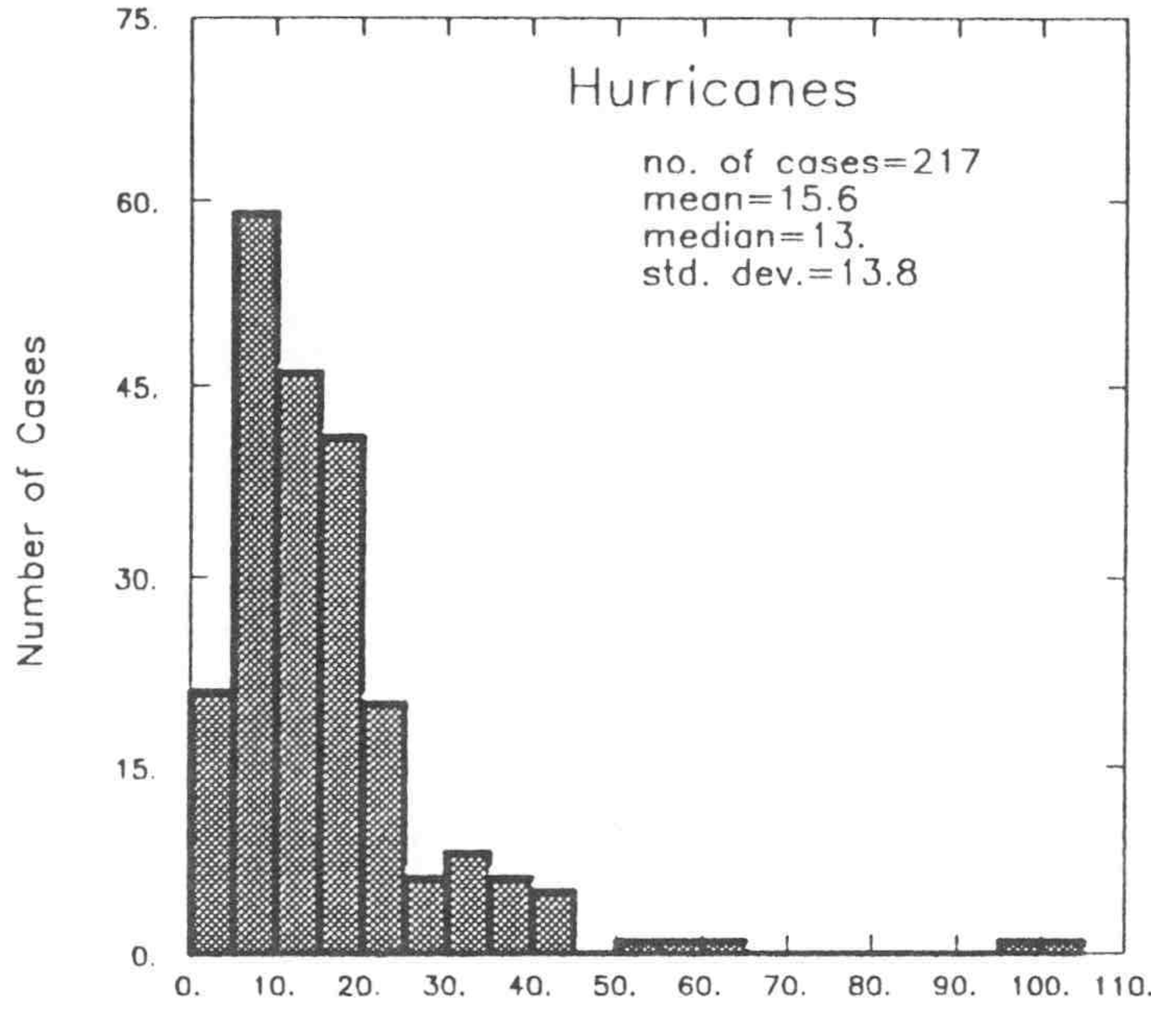


Figure 1-35. Deviations (in nmi) of NHC-determined positions from "best track" positions using visible spectra data or hurricanes for the 1981-86 Atlantic Basin hurricane season--by number of cases.

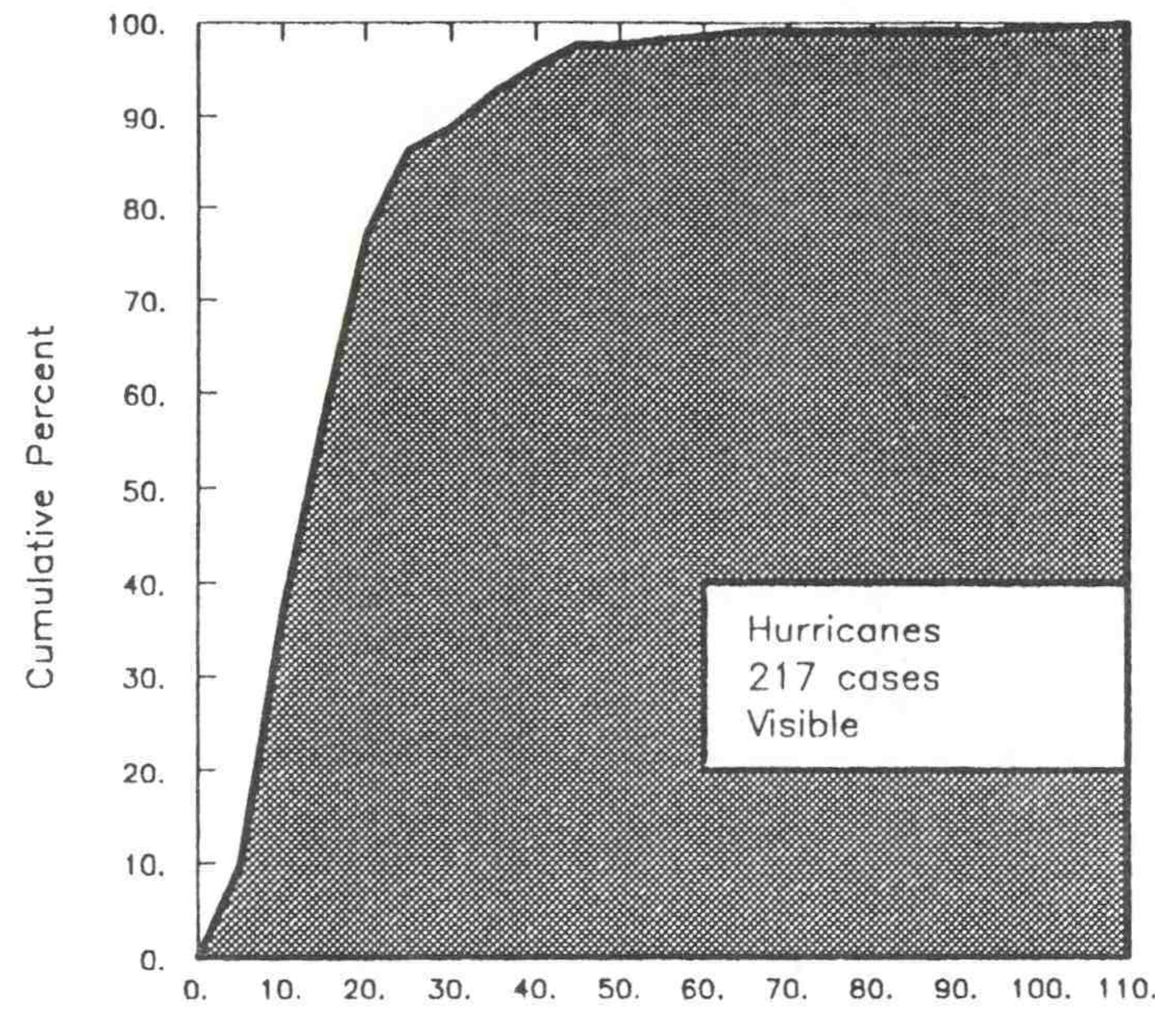


Figure 1-36. Deviations (in nmi) of NHC-determined positions from "best track" positions using visible spectra data for hurricane for the 1981-86 Atlantic Basin hurricane season--cumulative percentage.

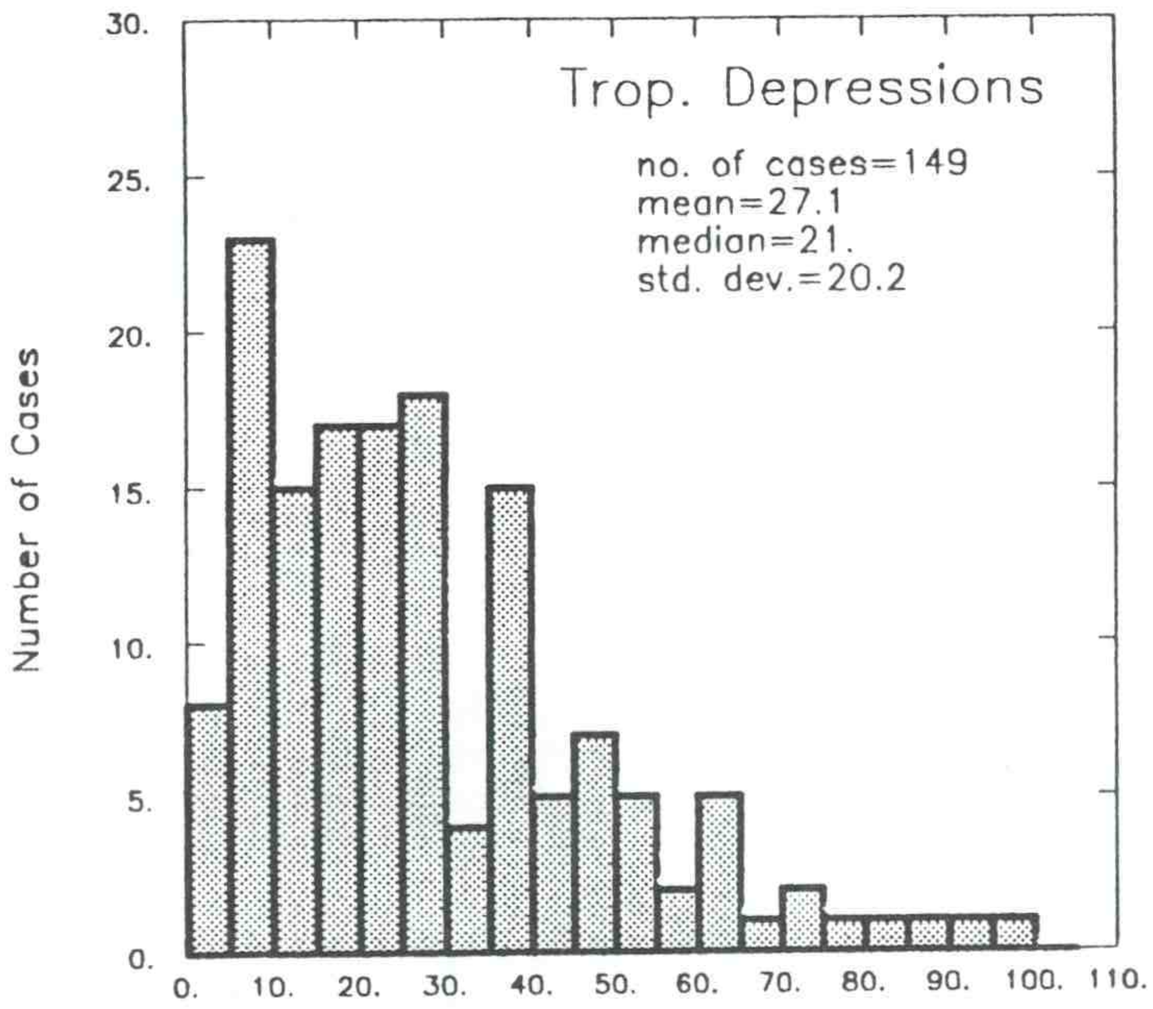


Figure 1-37. Deviations (in nmi) of NHC-determined positions from "best track" positions using infrared spectra data for tropical depressions for the 1981-86 Atlantic Basin hurricane season--by number of cases.

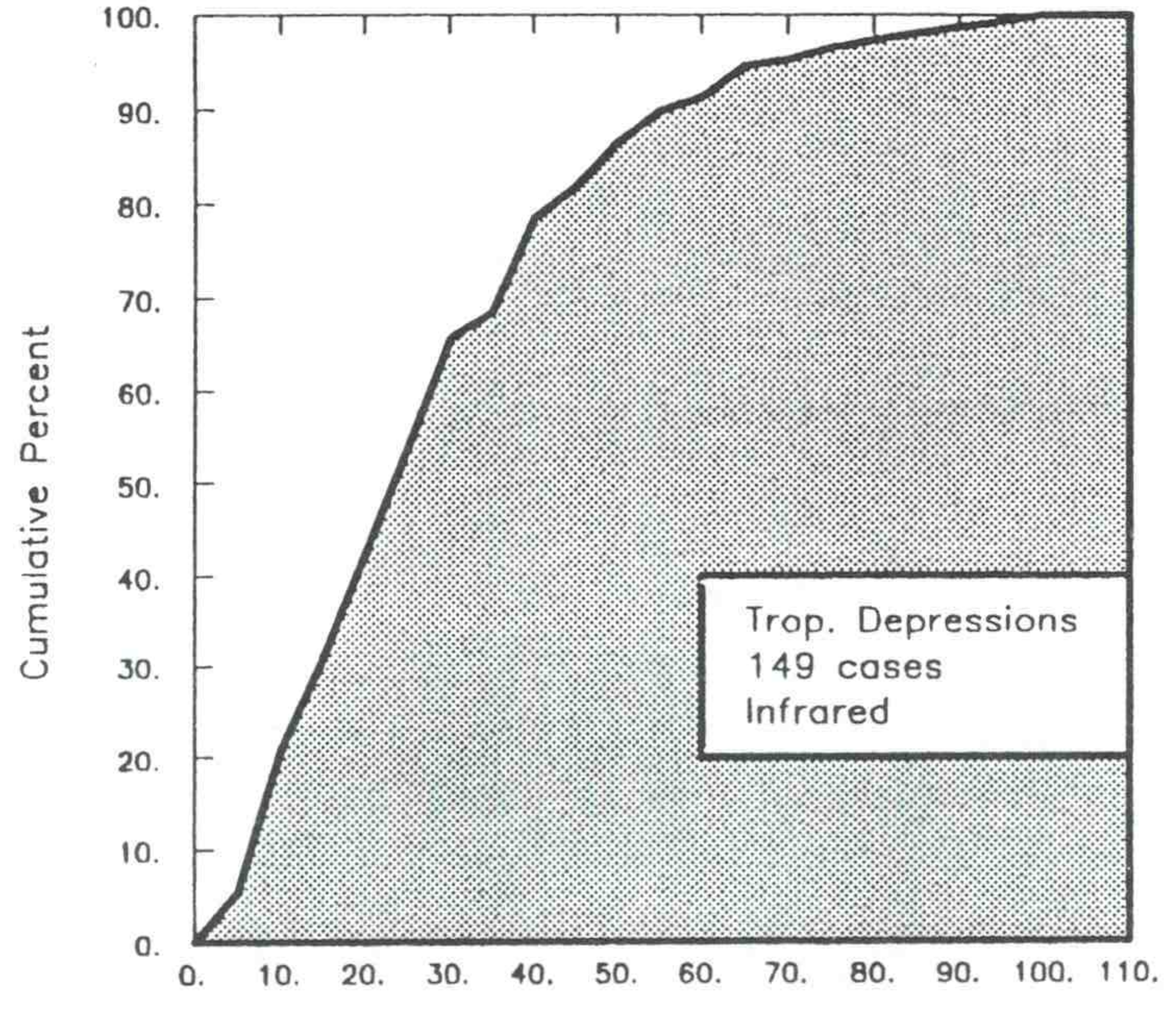


Figure 1-38. Deviations (in nmi) of NHC-determined positions from "best track" positions using infrared spectra data for tropical depressions for the 198Figure 1-86 Atlantic Basin hurricane season--cumulative percentage.

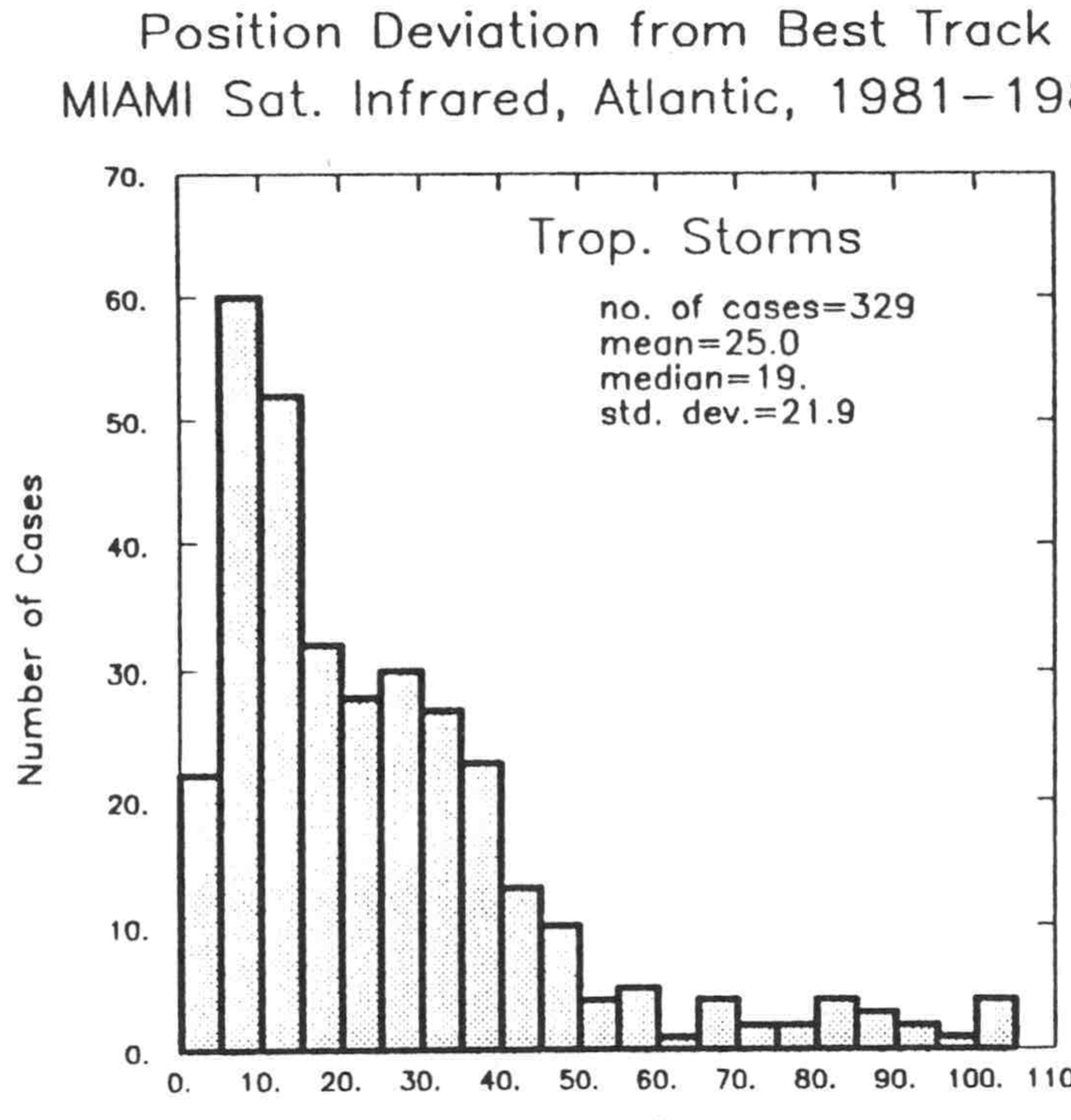


Figure 1-39. Deviations (in nmi) of NHC-determined positions from "best track" positions using infrared spectra data or tropical storms for the 1981-86 Atlantic Basin hurricane season--by number of cases.

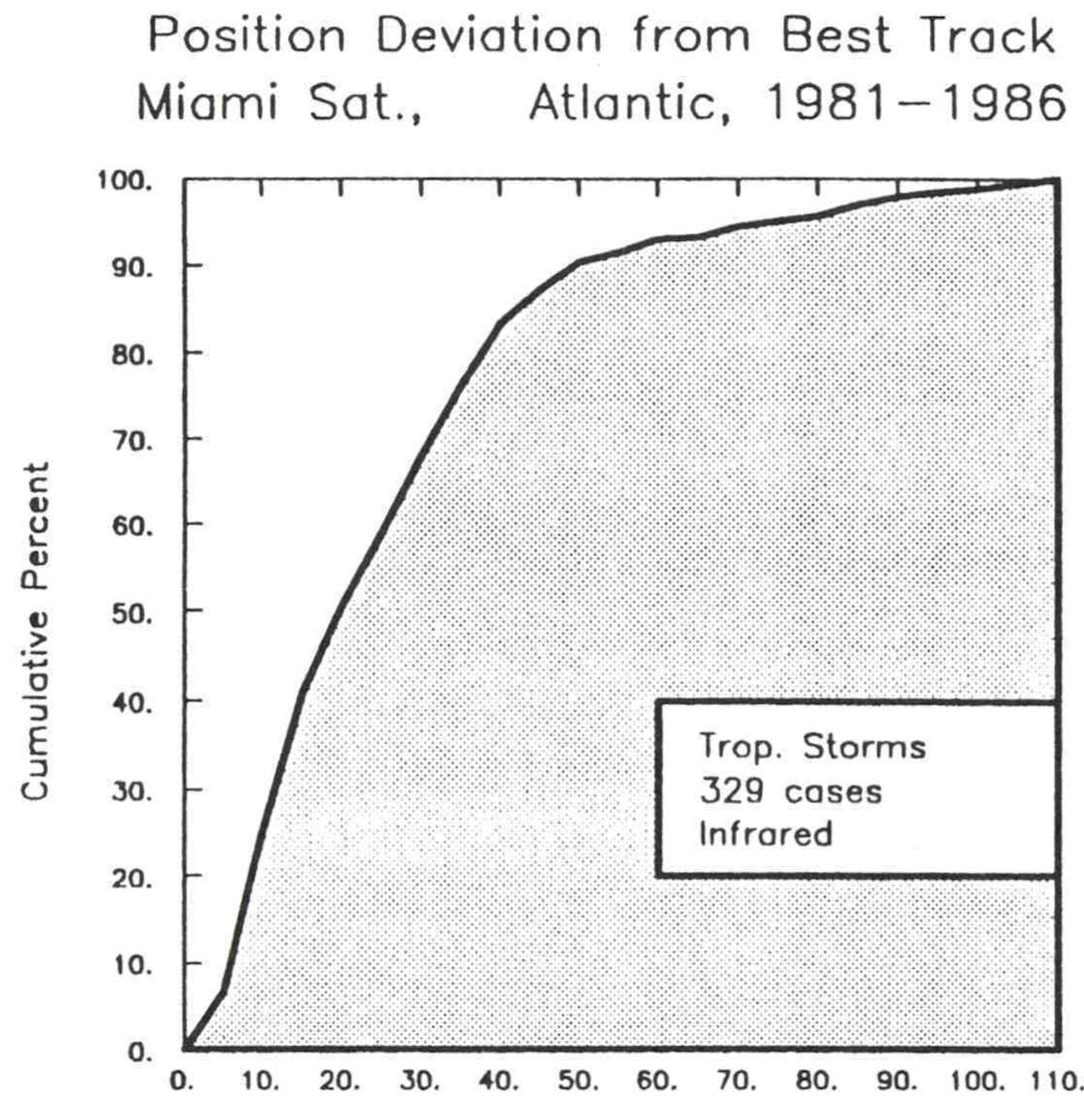


Figure 1-40. Deviations (in nmi) of NHC-determined positions from "best track" positions using infrared spectra data for tropical storms for the 1981-86 Atlantic Basin hurricane season--cumulative percentage.

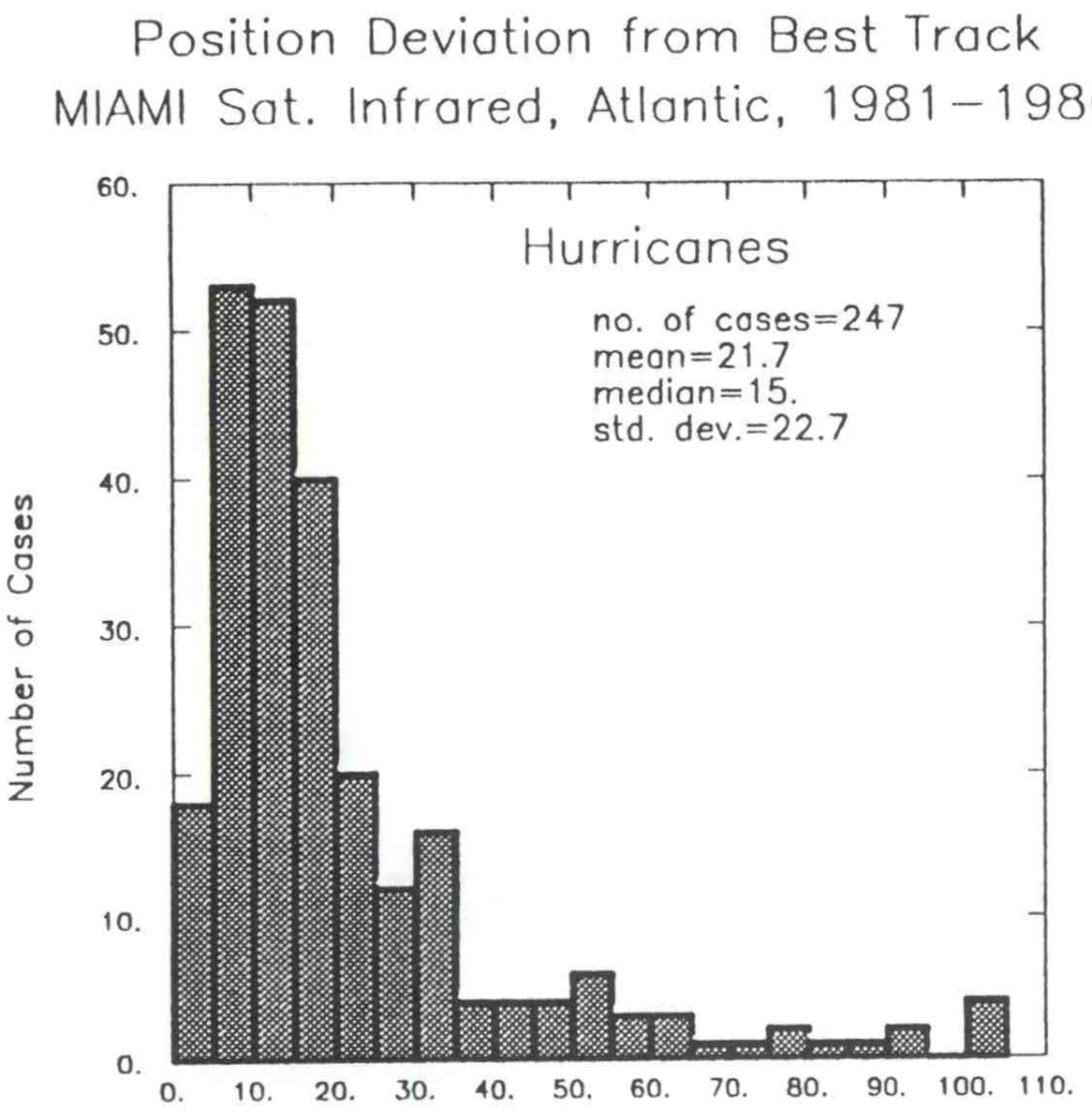


Figure 1-41. Deviations (in nmi) of NHC-determined positions from "best track" positions using infrared spectra data for hurricanes for the 1981-86 Atlantic Basin hurricane season--by number of cases.

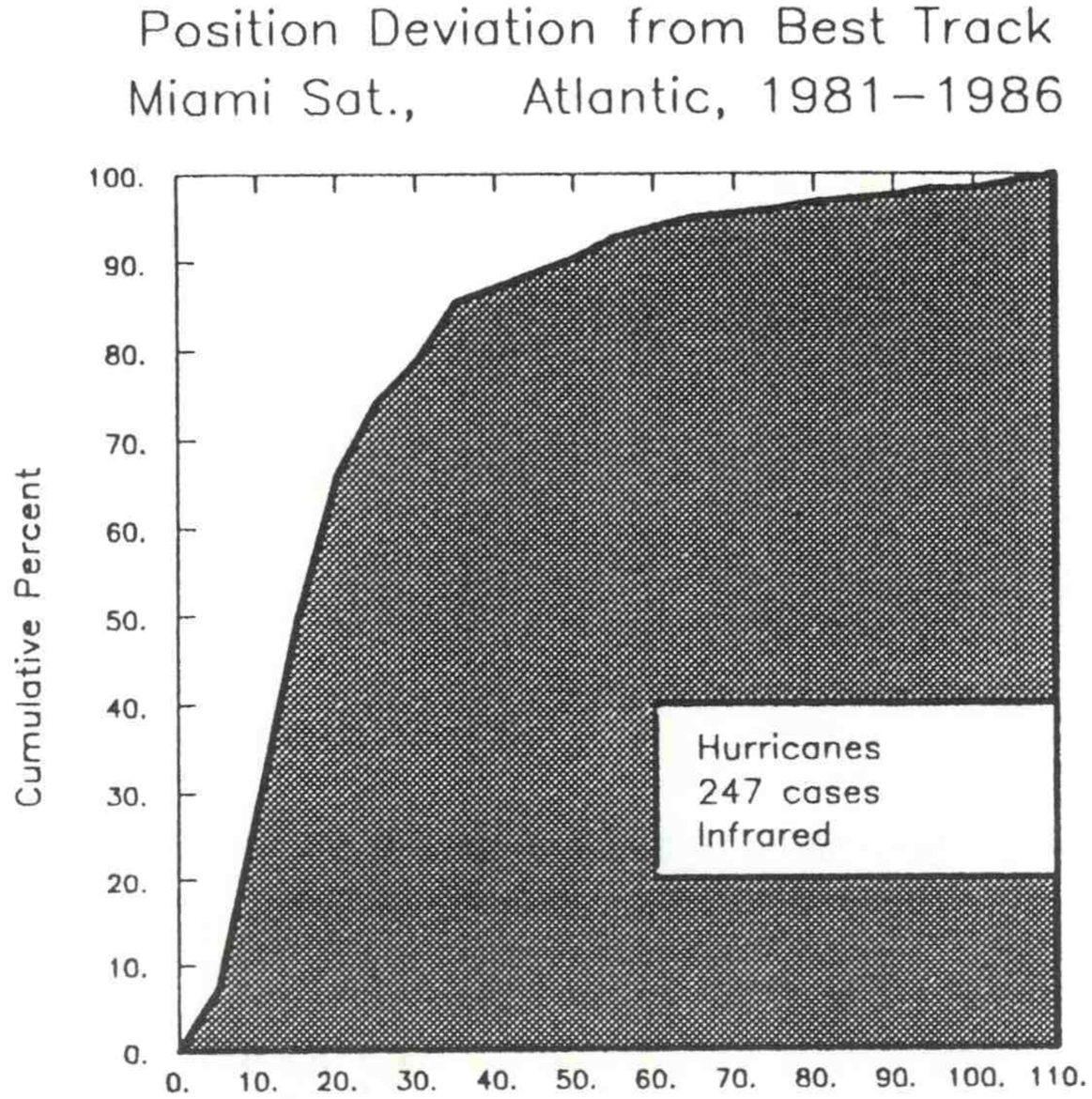


Figure 1-42. Deviations (in nmi) of NHC-determined positions from "best track" positions using infrared spectra data for hurricane for the 1981-86 Atlantic Basin hurricane season--cumulative percentage.

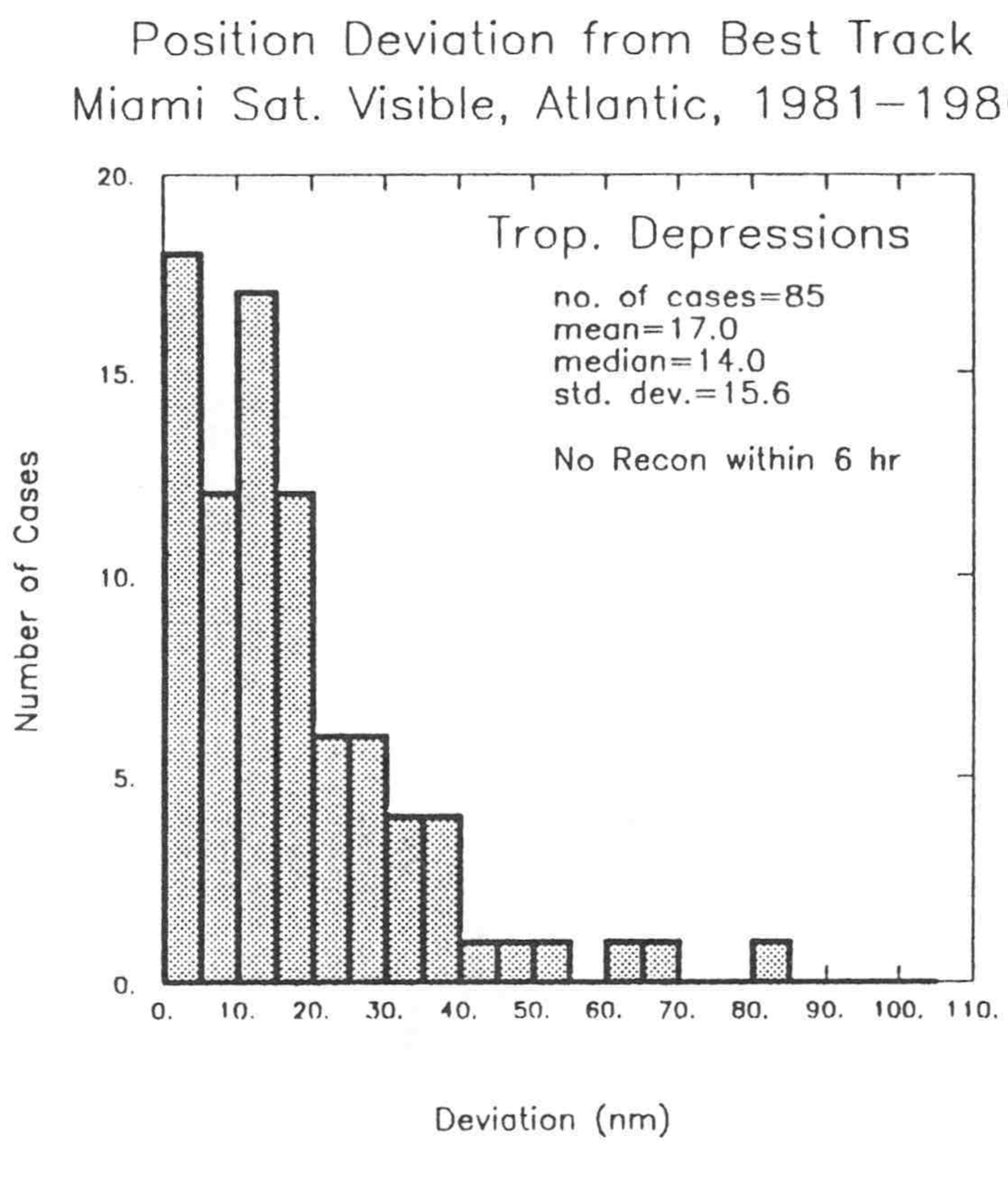


Figure 1-43. Deviations (in nmi) of NHC-determined positions from "best track" positions using visible spectra with no reconnaissance aircraft data available within 6 hours of image time. The sample is for tropical depressions for the 1981-86 Atlantic Basin hurricane season--by number of cases.

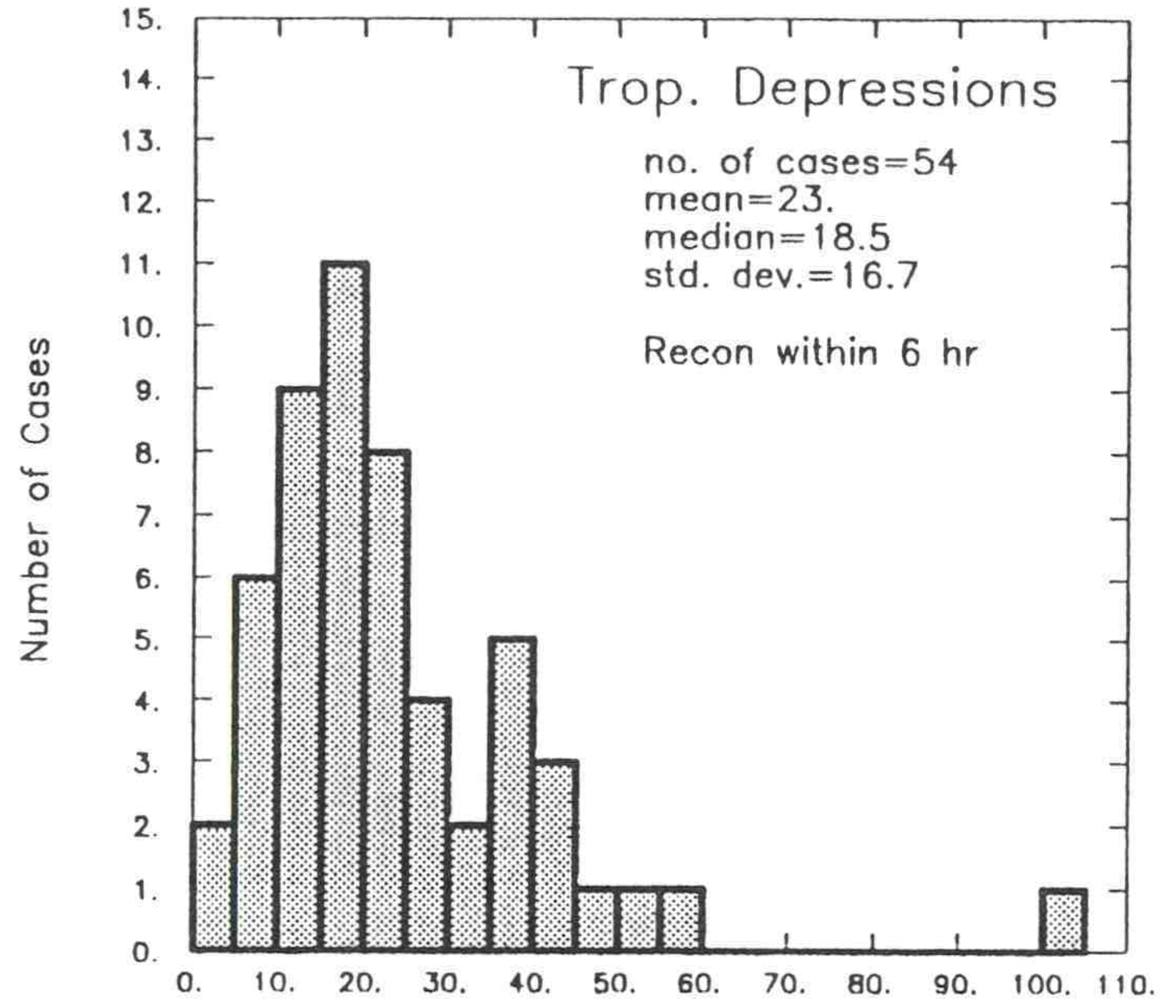


Figure 1-44. Deviations (in nmi) of NHC-determined positions from "best track" positions using visible spectra with no reconnaissance aircraft data available within 6 hours of image time. The sample is for tropical depressions for the 1981-86 Atlantic Basin hurricane season--cumulative percentage.

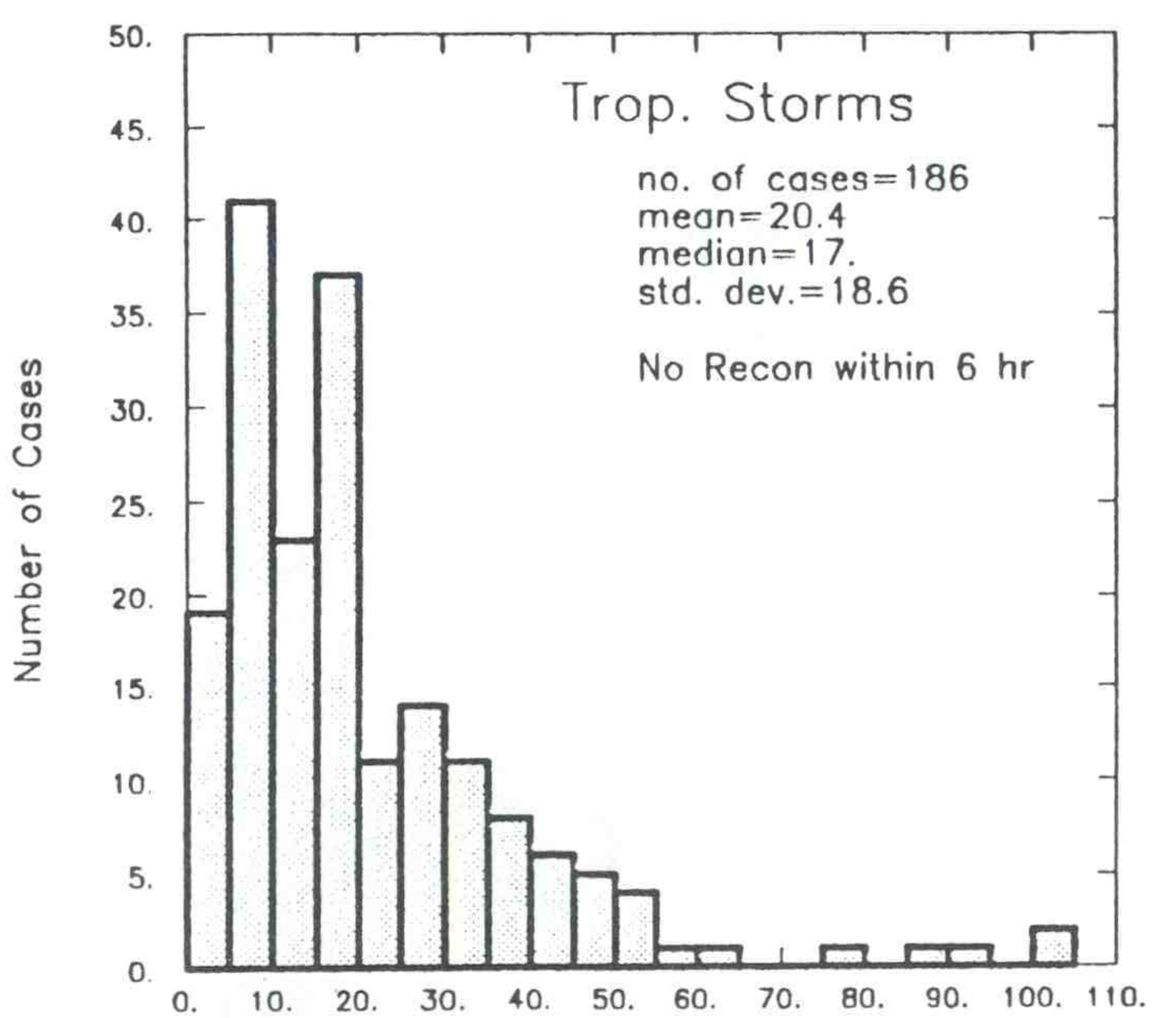


Figure 1-45. Deviations (in nmi) of NHC-deter positions from "best track" positions using visible spectra with no reconnaissance aircraft data available within 6 hours of image time. The sample is for tropical storms for the 1981-86 Atlantic Basin hurricane season--by number of cases.

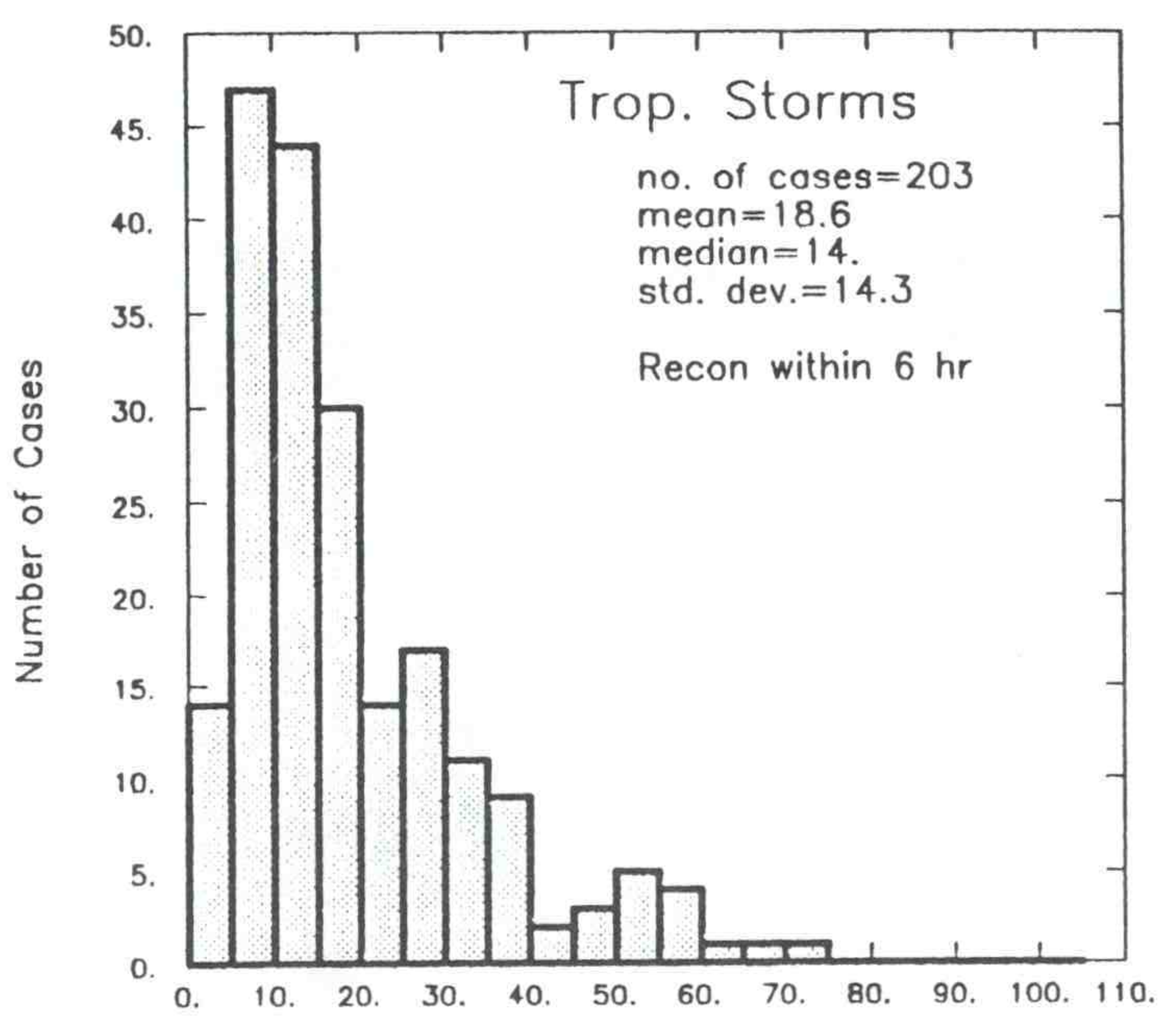


Figure 1-46. Deviations (in nmi) of NHC-determined positions from "best track" positions using visible spectra with no reconnaissance aircraft data available within 6 hours of image time. The sample is for tropical storms for the 1981-86 Atlantic Basin hurricane season--cumulative percentage.

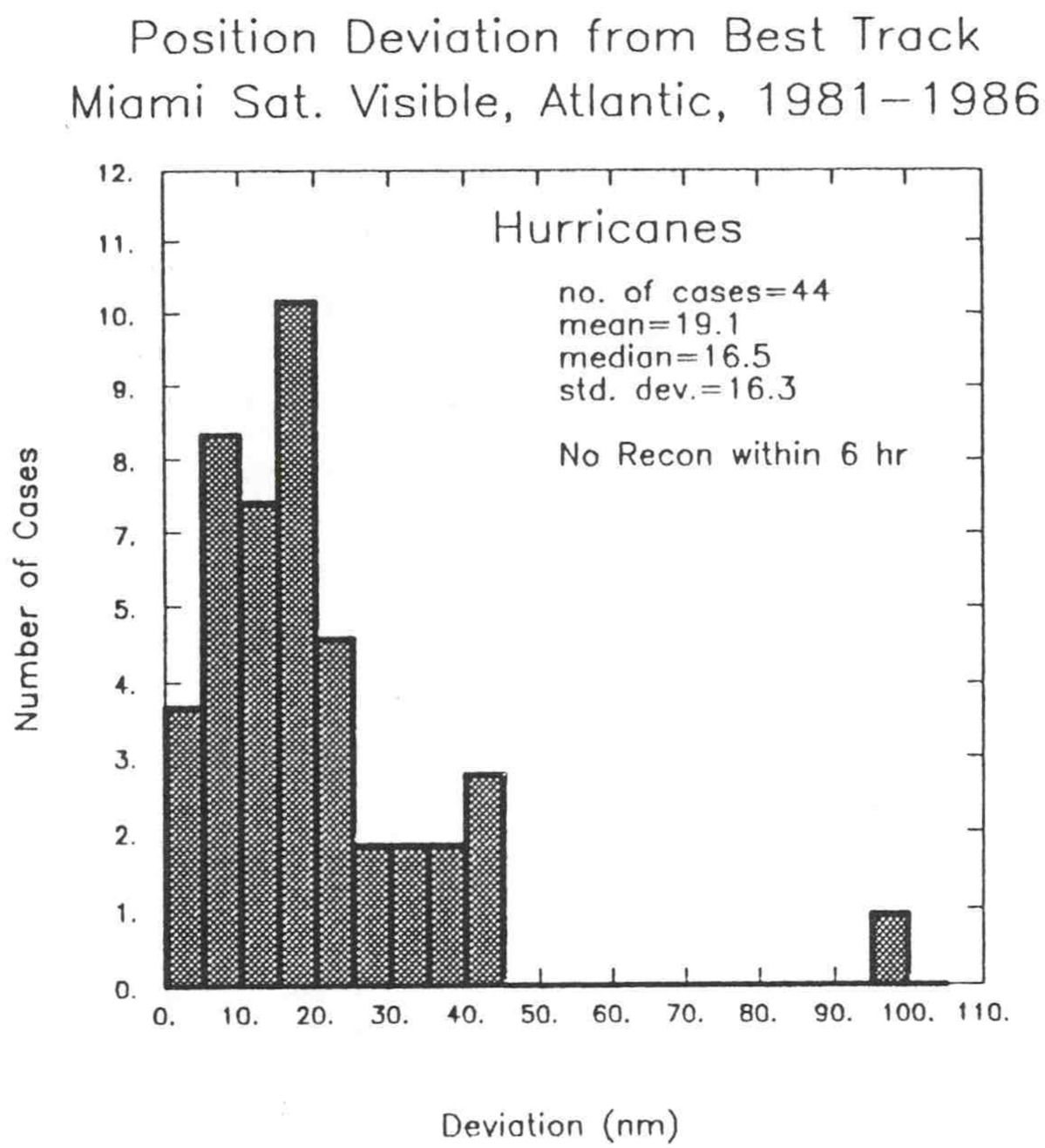


Figure 1-47. Deviations (in nmi) of NHC-determined positions from "best track" positions using visible spectra with no reconnaissance aircraft data available within 6 hours of image time. The sample is for hurricanes for the 1981-86 Atlantic Basin hurricane season--by number of cases.

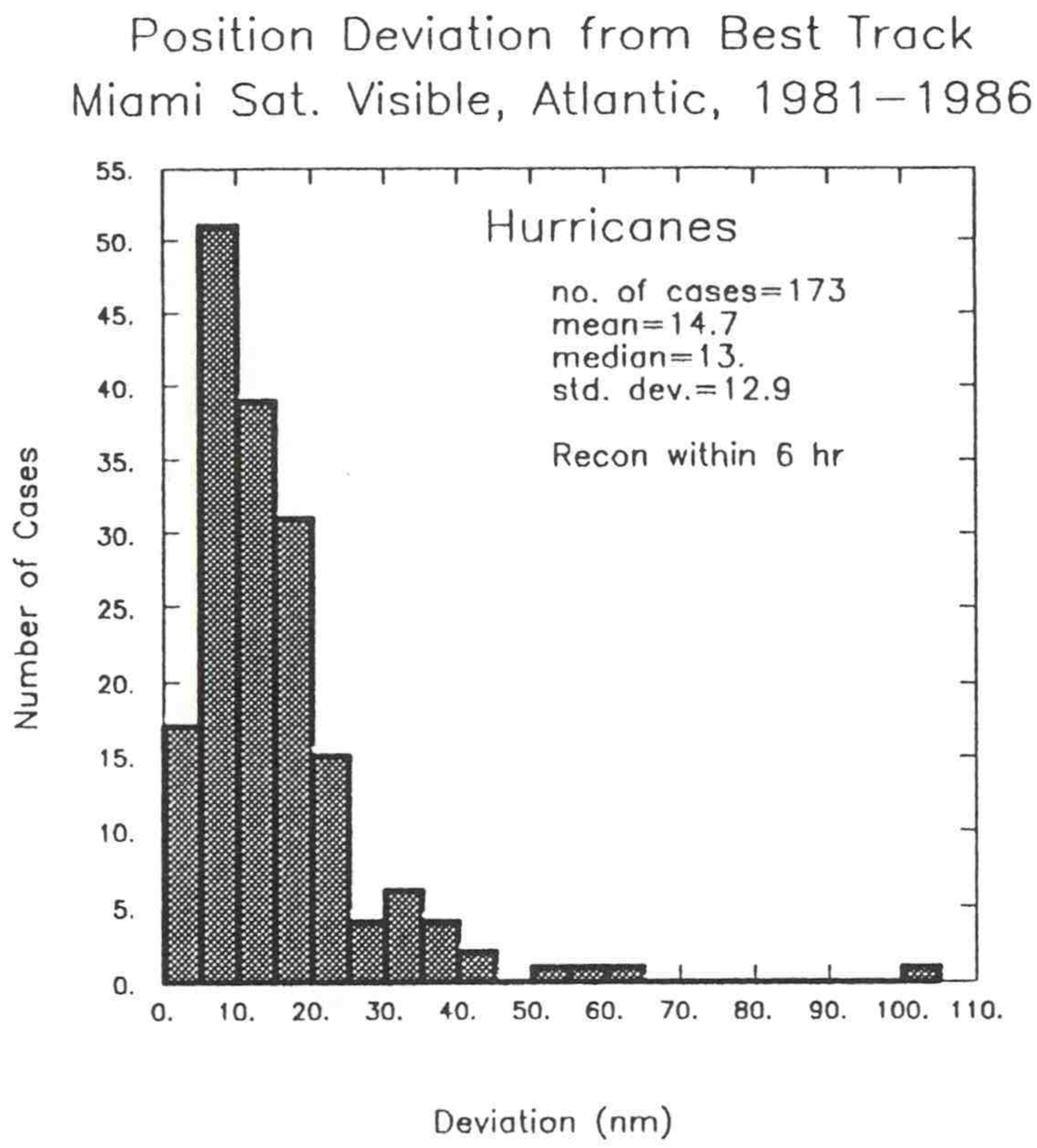


Figure 1-48. Deviations (in nmi) of NHC-determined positions from "best track" positions using visible spectra with no reconnaissance aircraft data available within 6 hours of image time. The sample is for hurricane for the 1981-86 Atlantic Basin hurricane season--cumulative percentage.

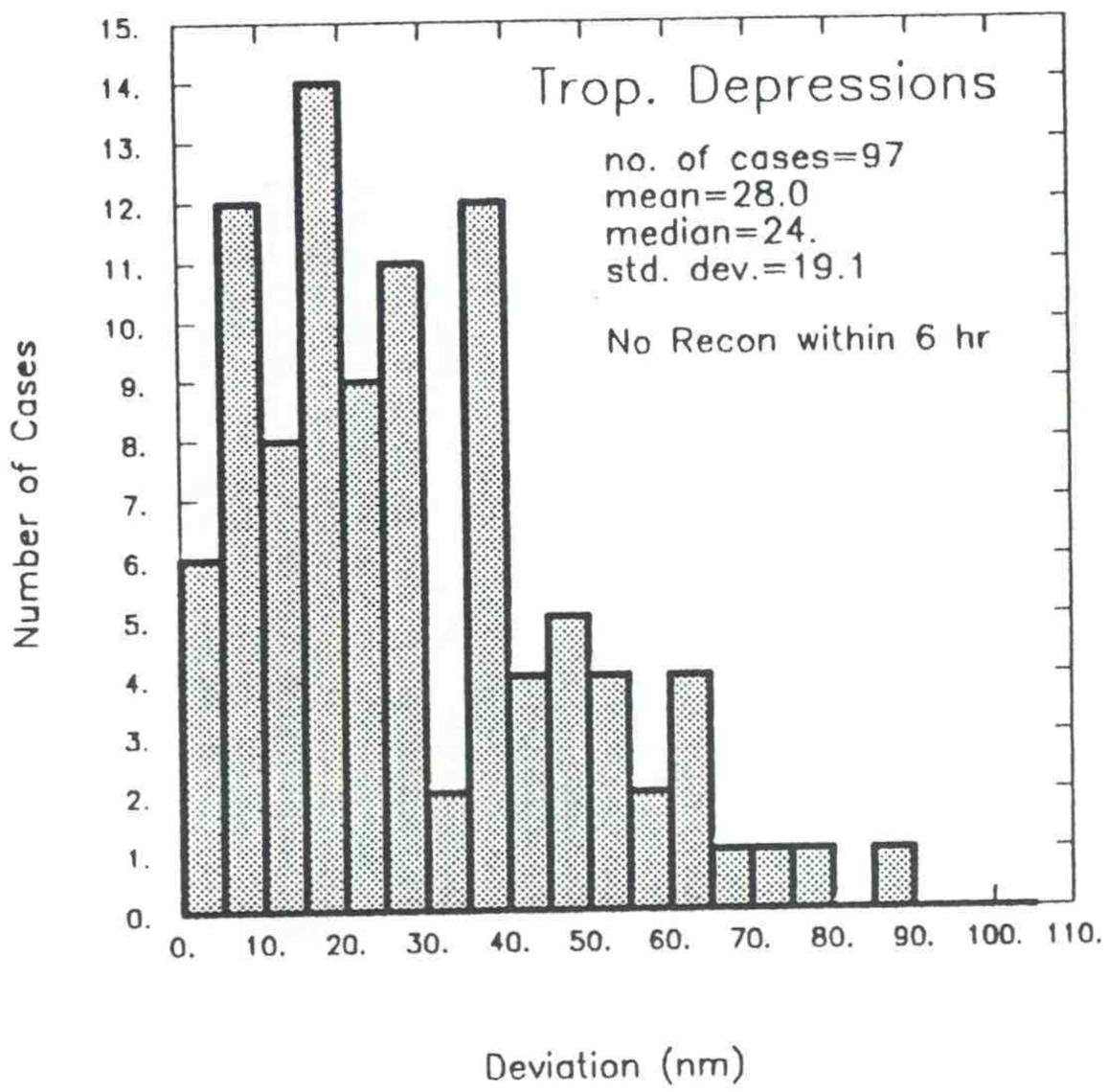


Figure 1-49. Deviations (in nmi) of NHC-determined positions from "best track" positions using infrared spectra with no reconnaissance aircraft data available within 6 hours of image time. The sample is for tropical depressions for the 1981-86 Atlantic Basin hurricane season--by number of cases.

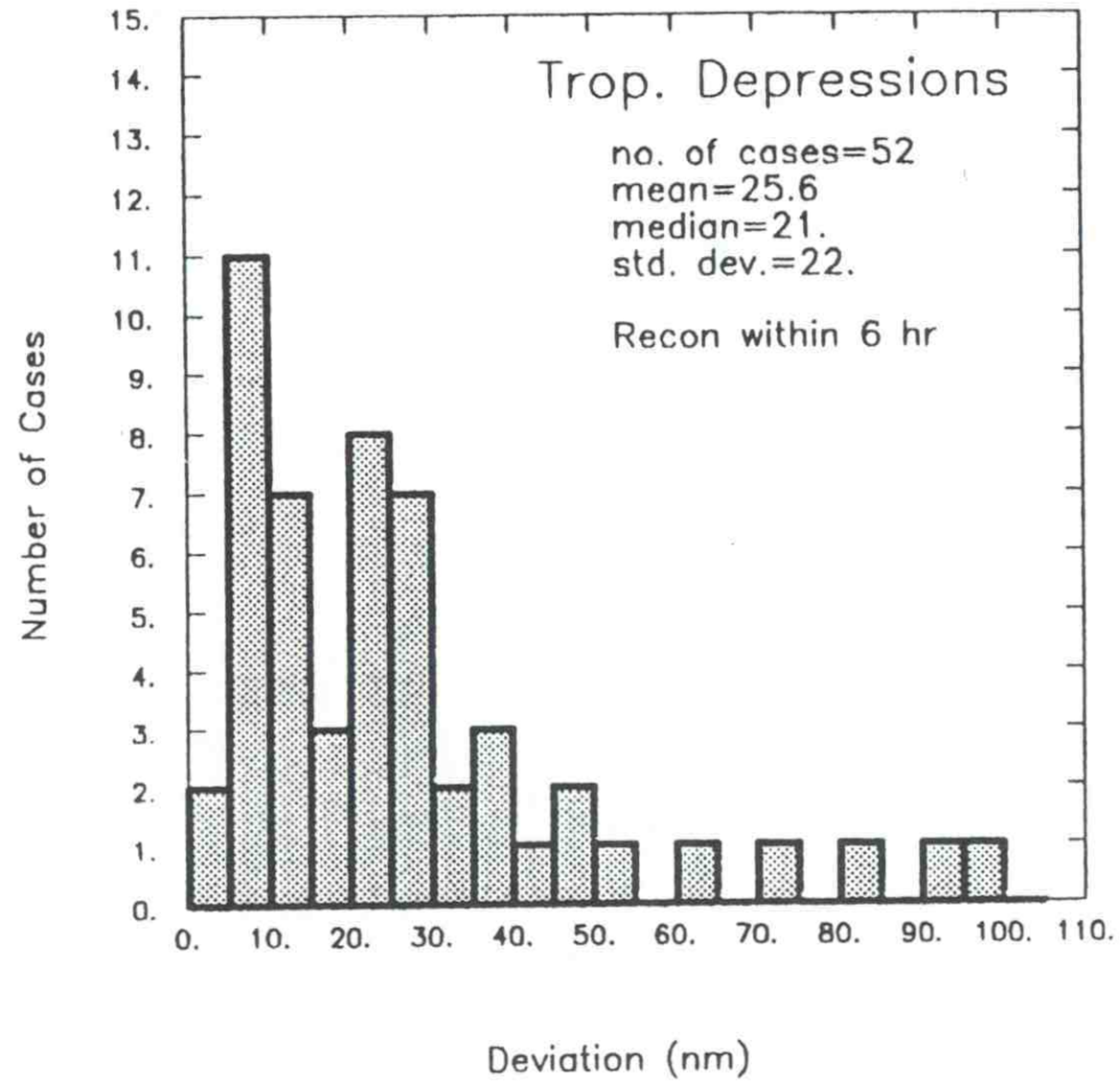


Figure 1-50. Deviations (in nmi) of NHC-determined positions from "best track" positions using infrared spectra with no reconnaissance aircraft data available within 6 hours of image time. The sample is for tropical depressions for the 1981-86 Atlantic Basin hurricane season--cumulative percentage.

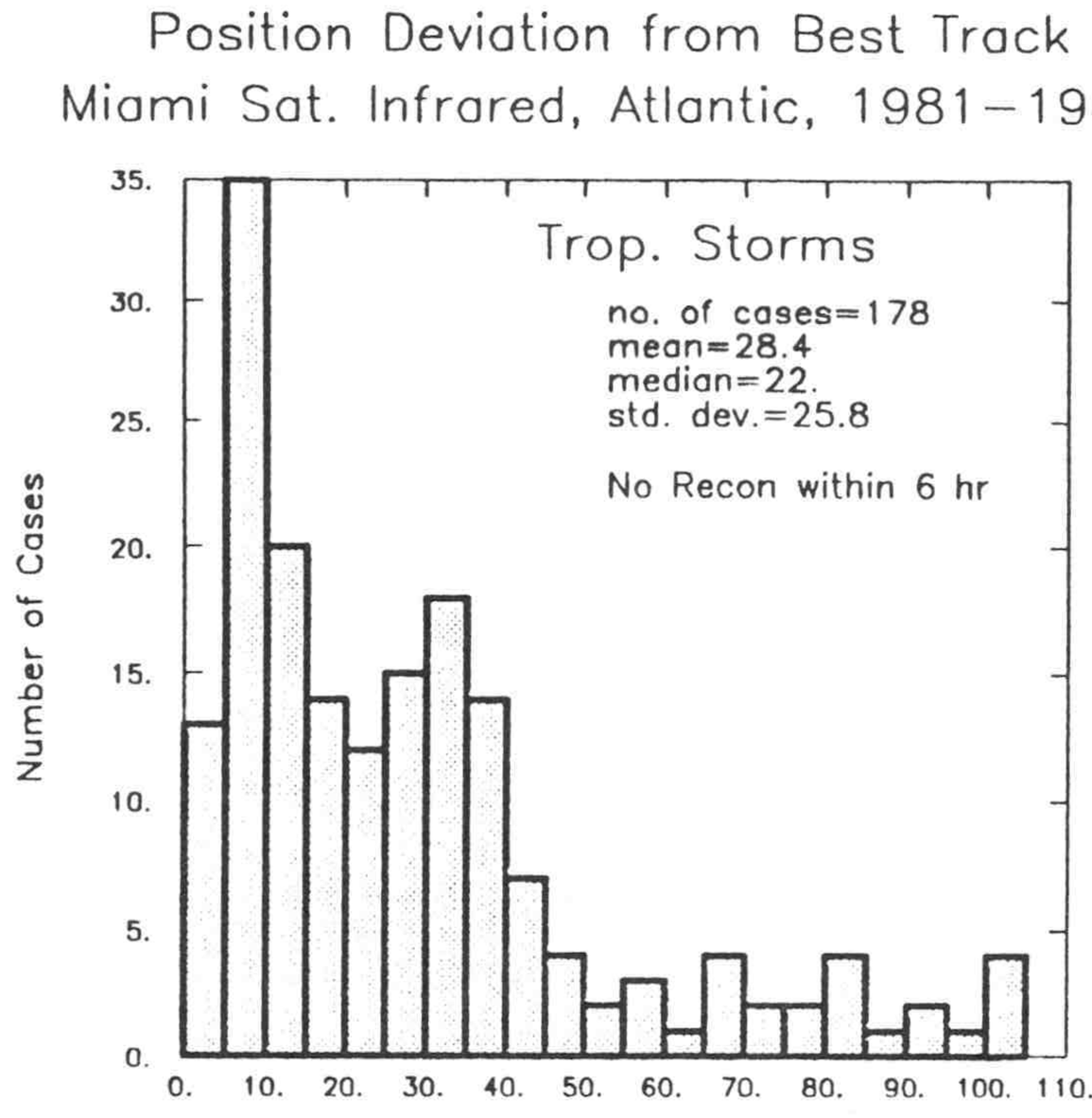


Figure 1-51. Deviations (in nmi) of NHC-determined positions from "best track" positions using infrared spectra with no reconnaissance aircraft data available within 6 hours of image time. The sample is for tropical storms for the 1981-86 Atlantic Basin hurricane season.

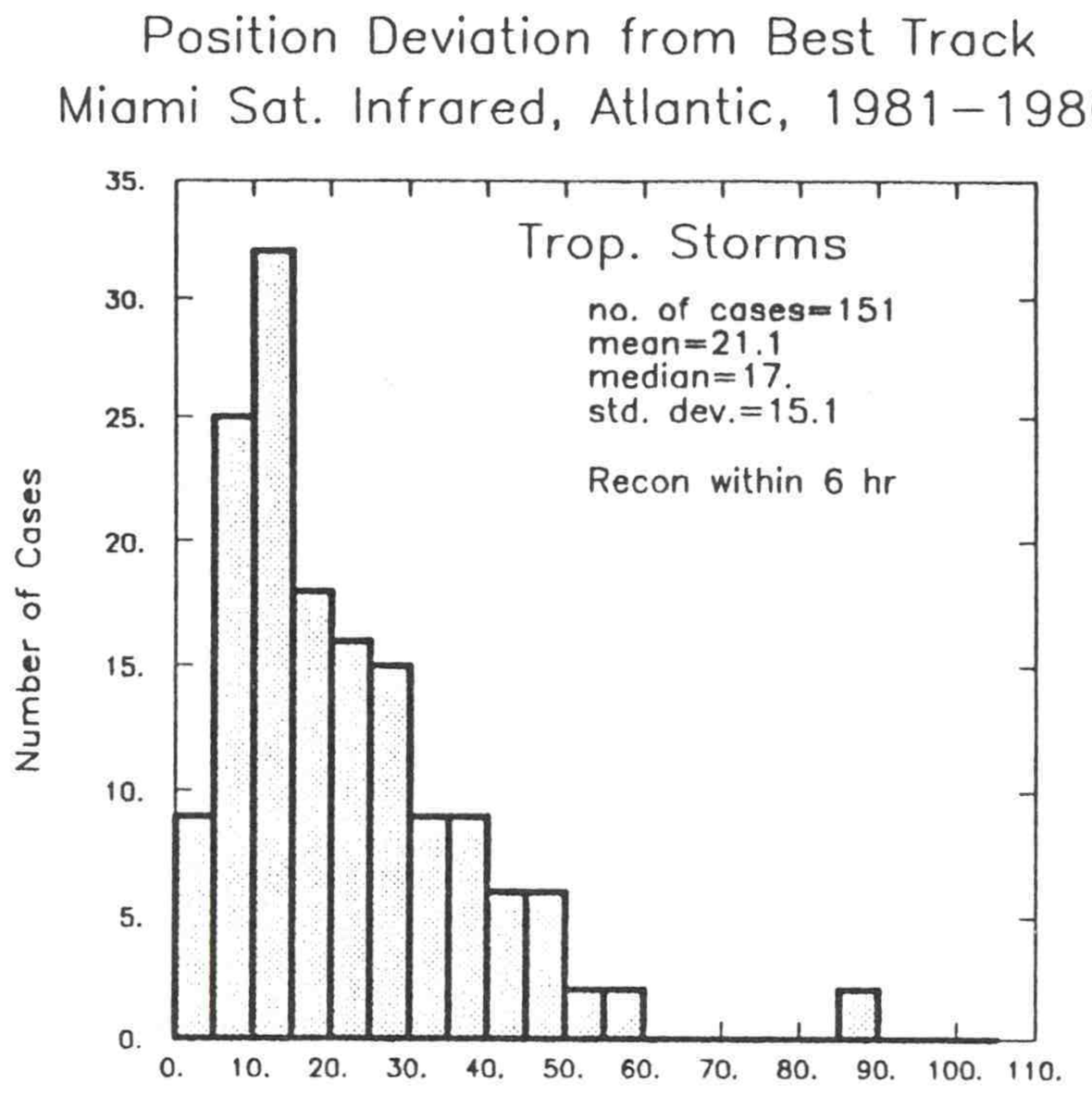


Figure 1-52. Deviations (in nmi) of NHC-determined positions from "best track" positions using infrared spectra with no reconnaissance aircraft data available within 6 hours of image time. The sample is for tropical storms for the 1981-86 Atlantic Basin hurricane season.

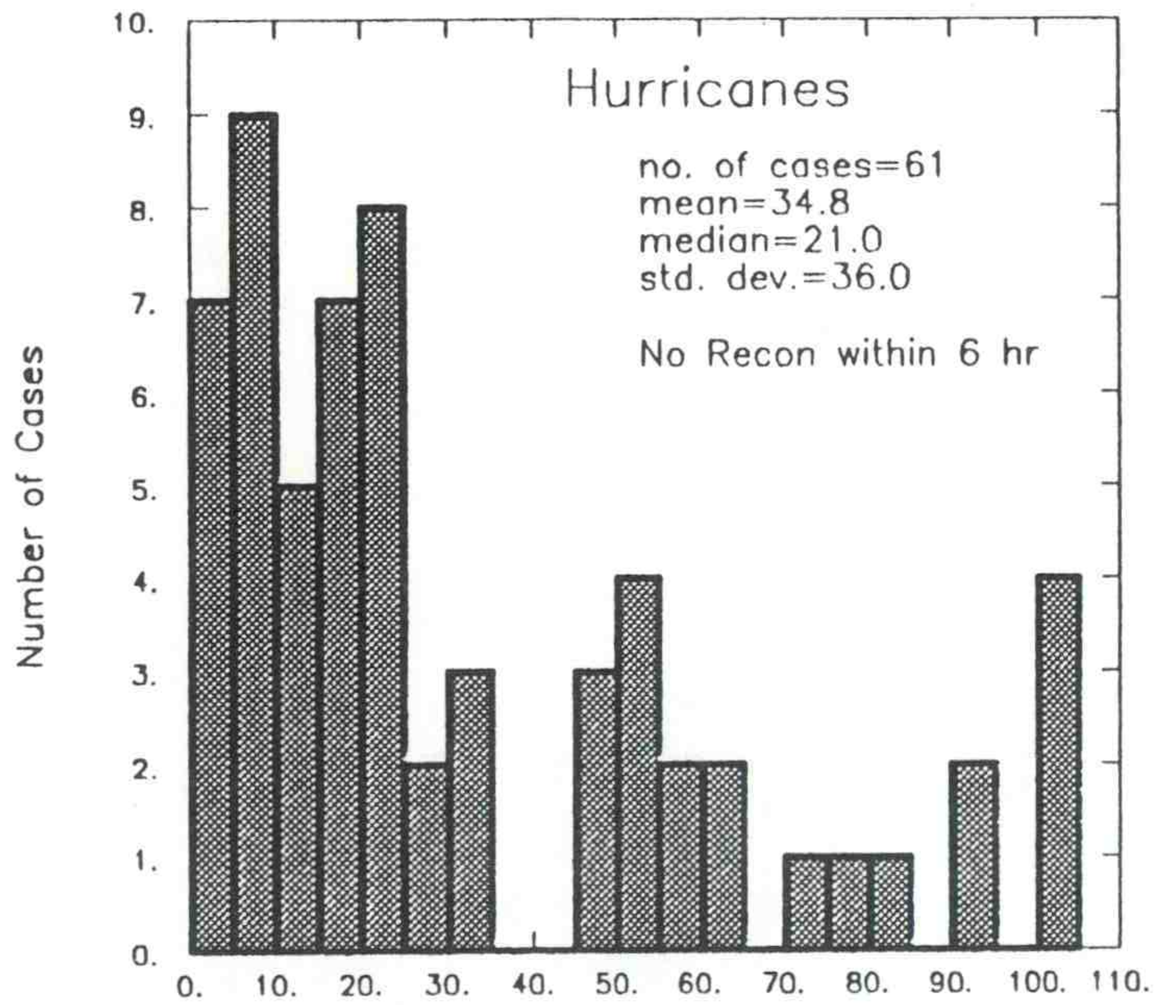


Figure 1-53. Deviations (in nmi) of NHC-determined positions from "best track" positions using infrared spectra with no reconnaissance aircraft data available within 6 hours of image time. The sample is for hurricanes for the 1981-86 Atlantic Basin hurricane season.

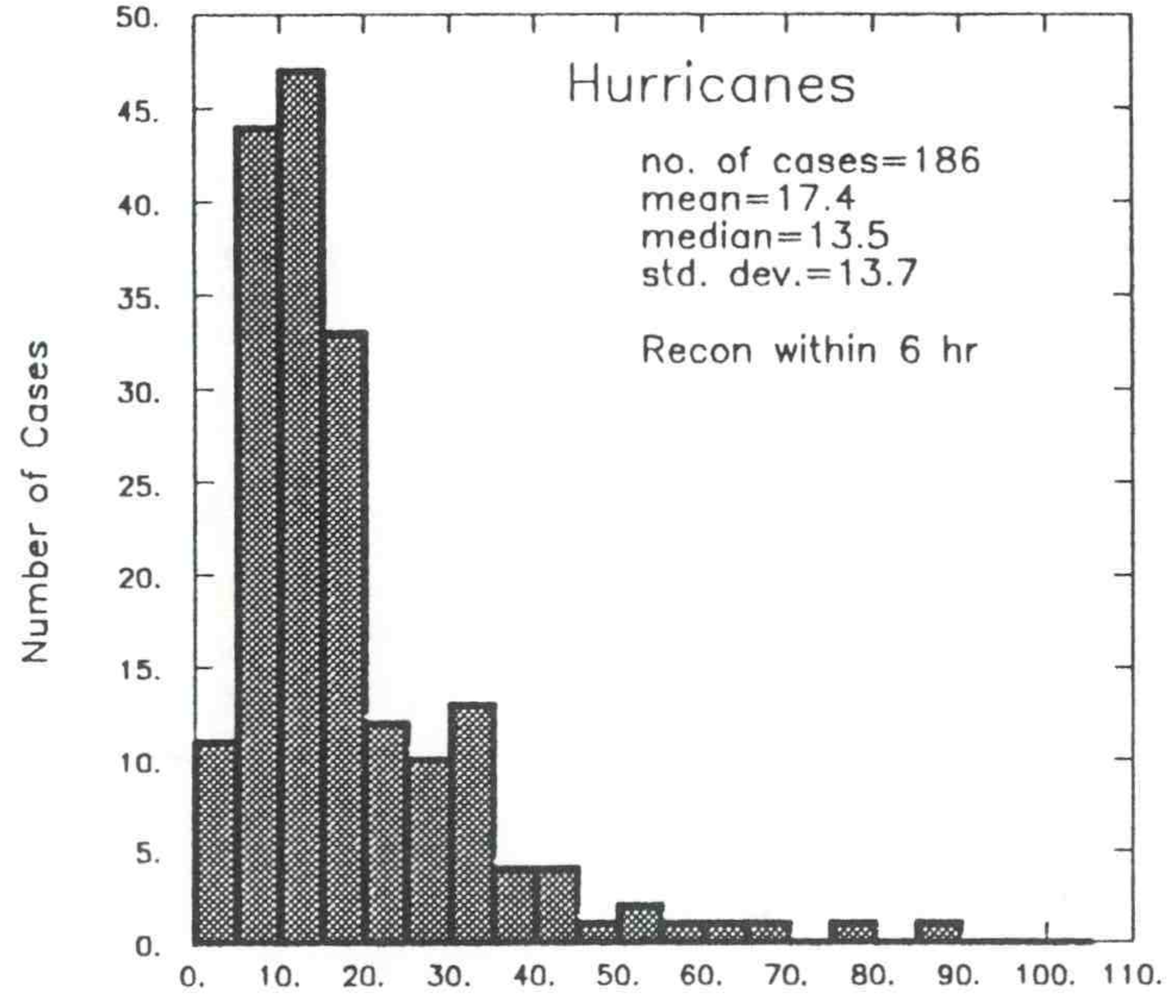


Figure 1-54. Deviations (in nmi) of NHC-determined positions from "best track" positions using infrared spectra with no reconnaissance aircraft data available within 6 hours of image time. The sample is for hurricanes for the 1981-86 Atlantic Basin hurricane season.

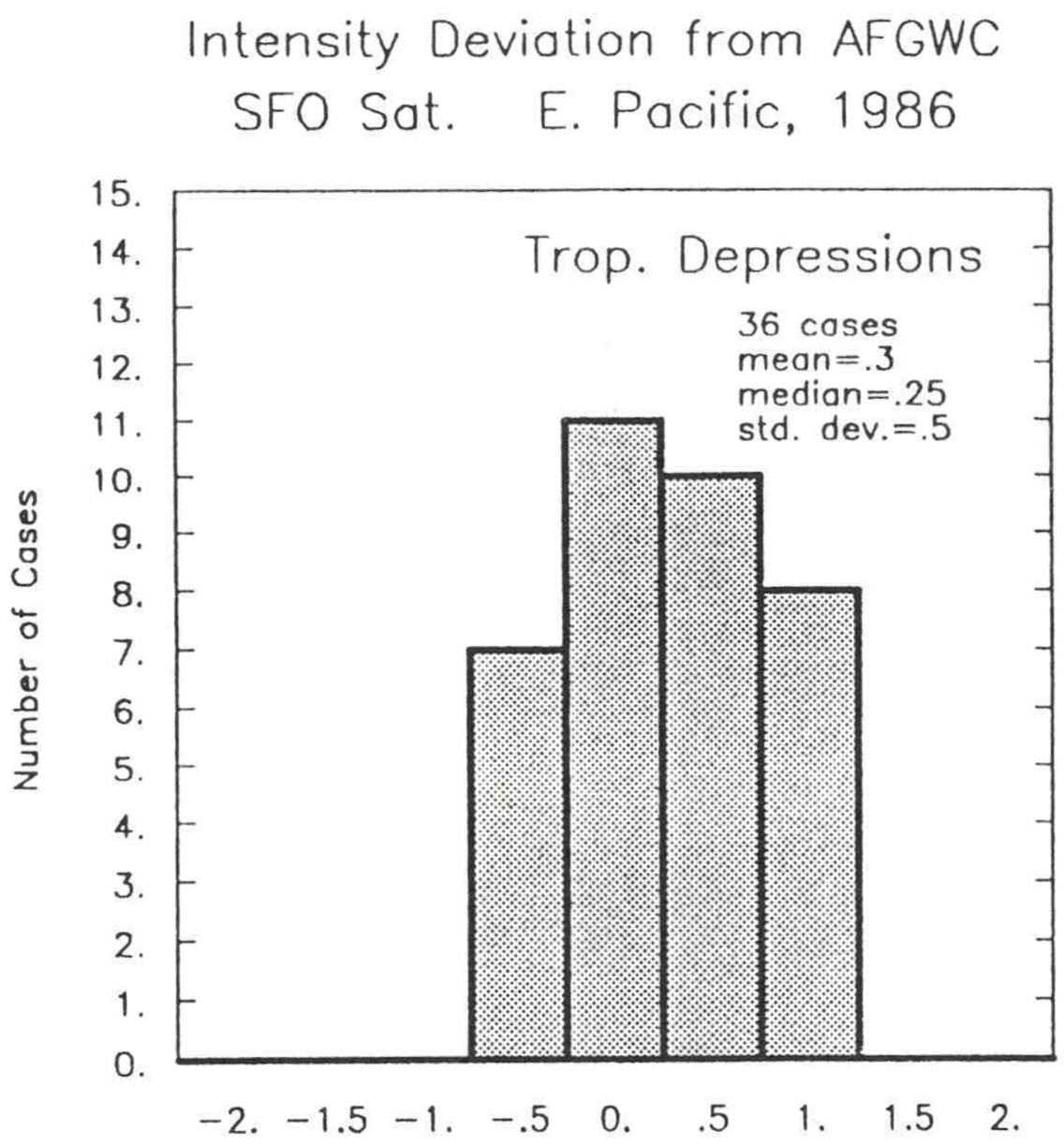


Figure 1-55. Intensity estimate differences (Current Intensity Number) for the EPHC versus AFGWC. This sample is for tropical depressions for the 1986 Eastern Pacific hurricane season.

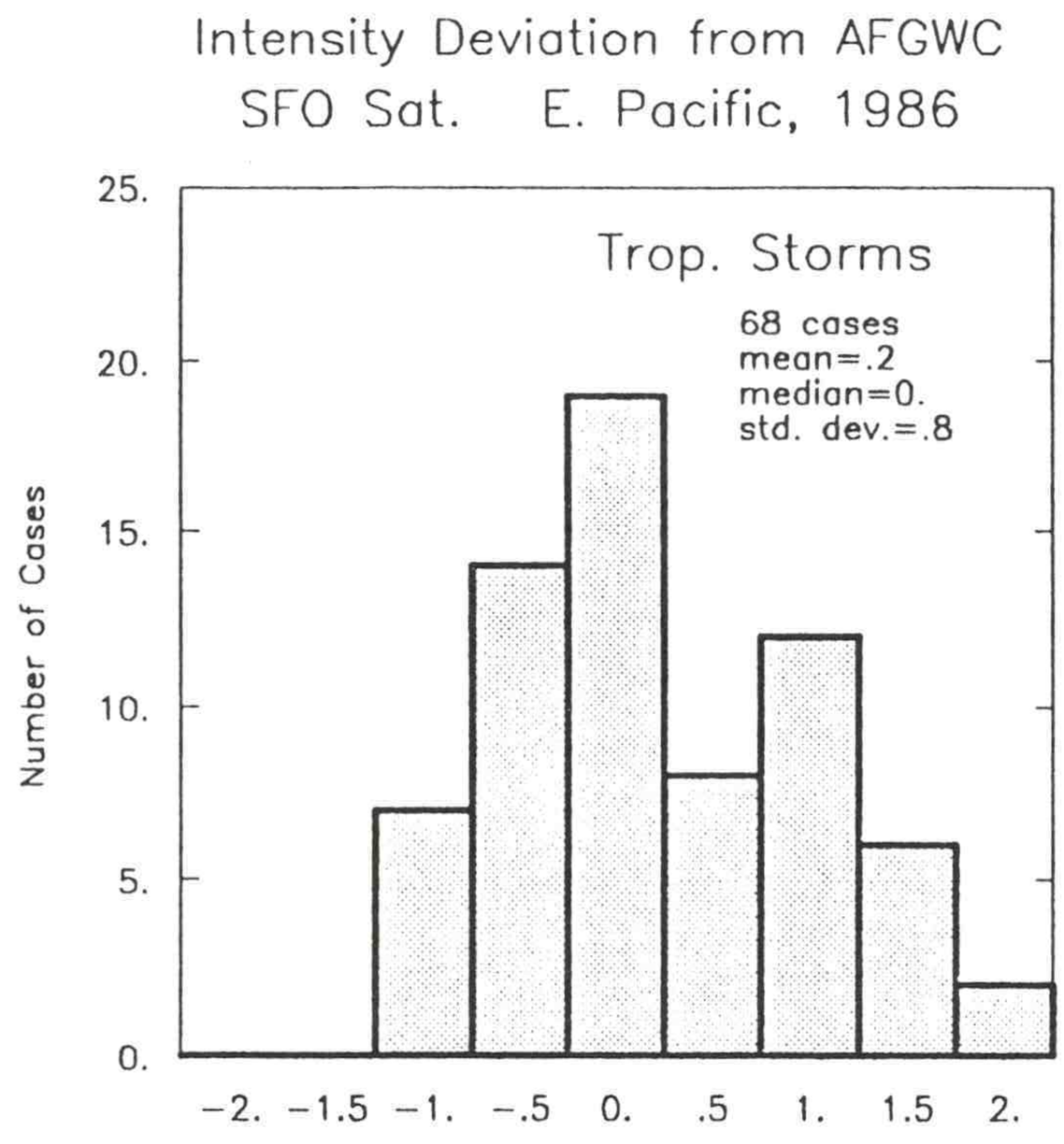


Figure 1-56. Intensity estimate differences (Current Intensity Number) for the EPHC versus AFGWC. This sample is for tropical storms for the 1986 Eastern Pacific hurricane season.

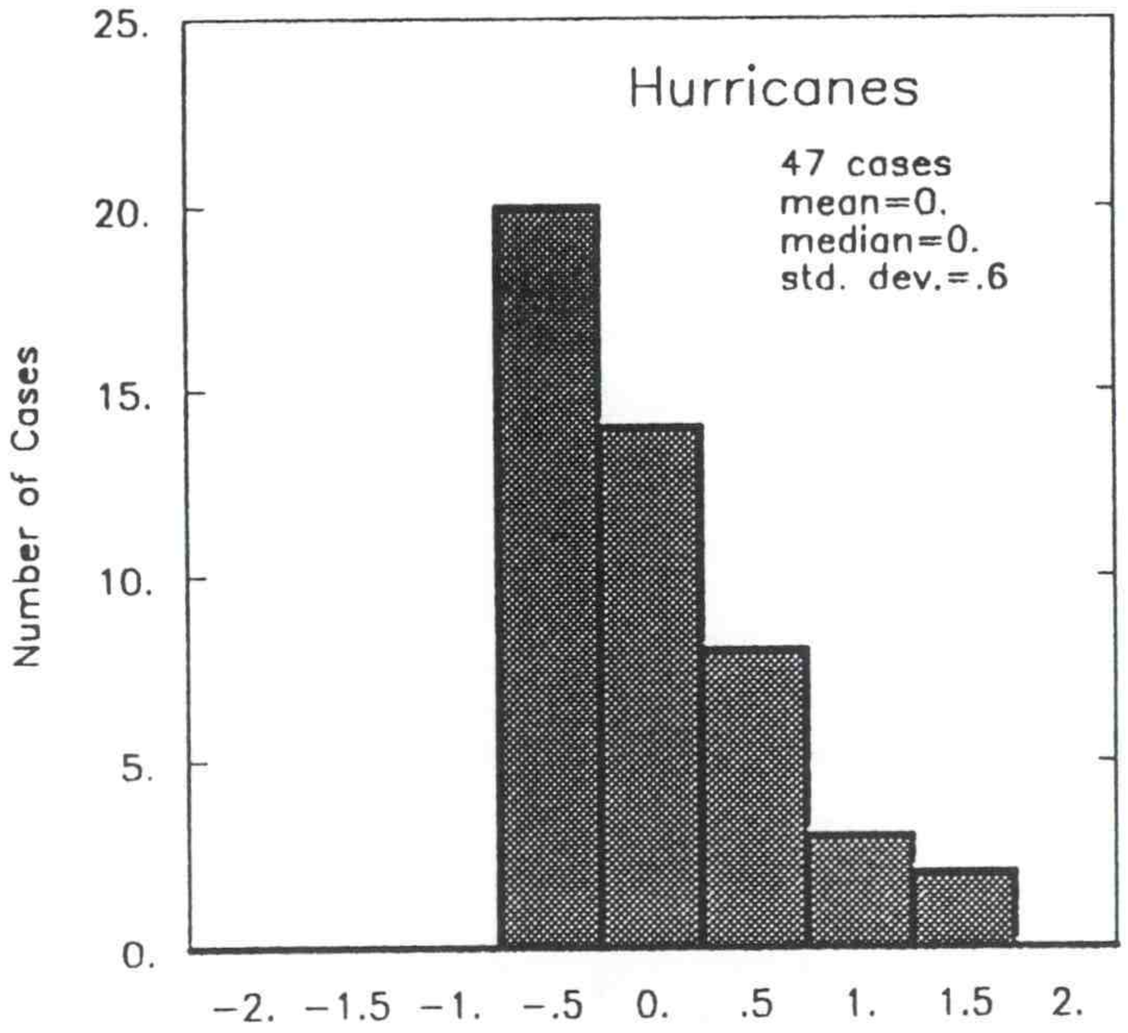


Figure 1-57. Intensity estimate differences (Current Intensity Number) for the EPHC versus AFGWC. This sample is for hurricanes for the 1986 Eastern Pacific hurricane season.

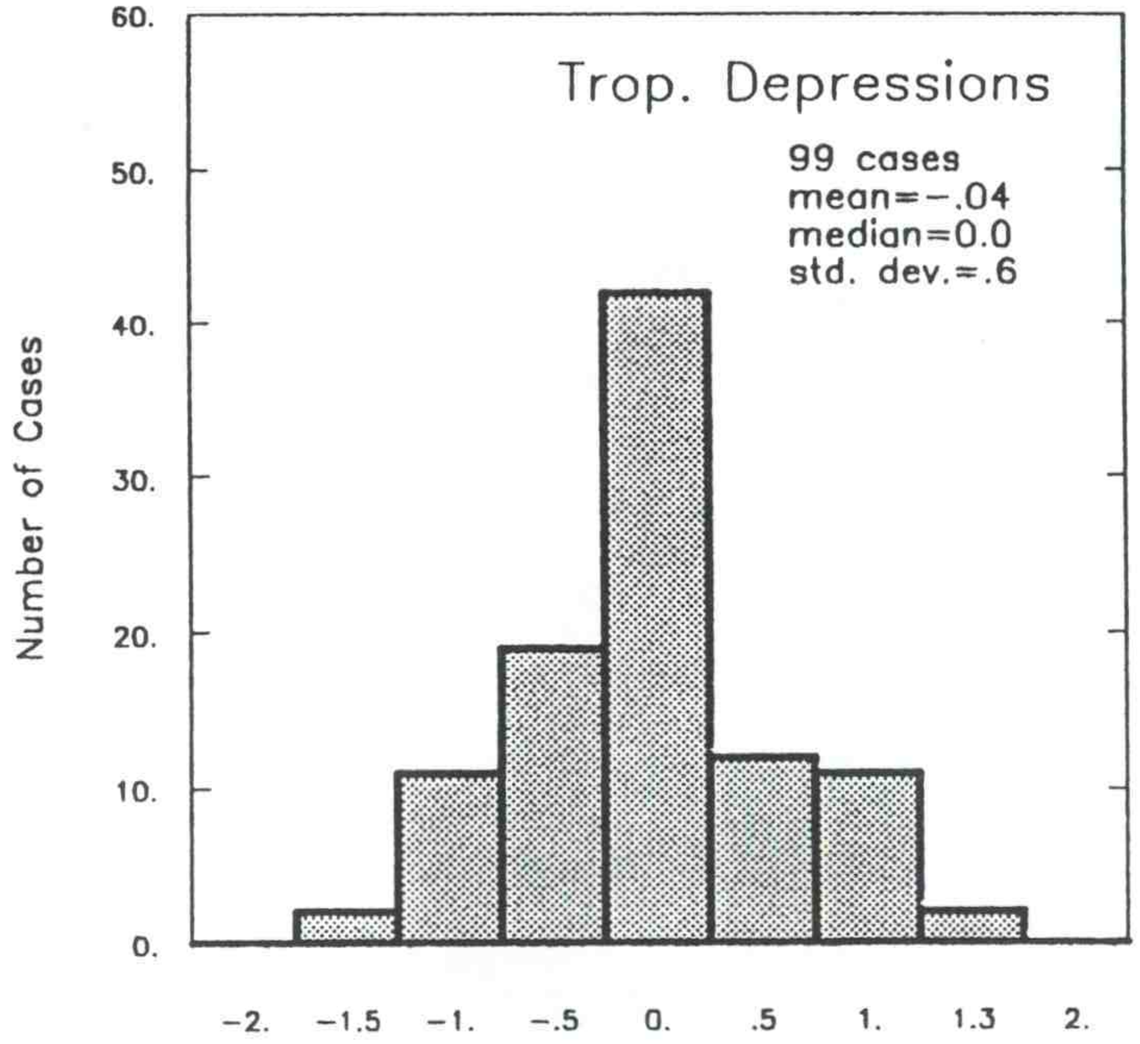


Figure 1-58. Intensity estimate differences (Current Intensity Number) for AFGWC versus the NHC. This sample is for tropical depressions for the 1986 Eastern Pacific hurricane season.

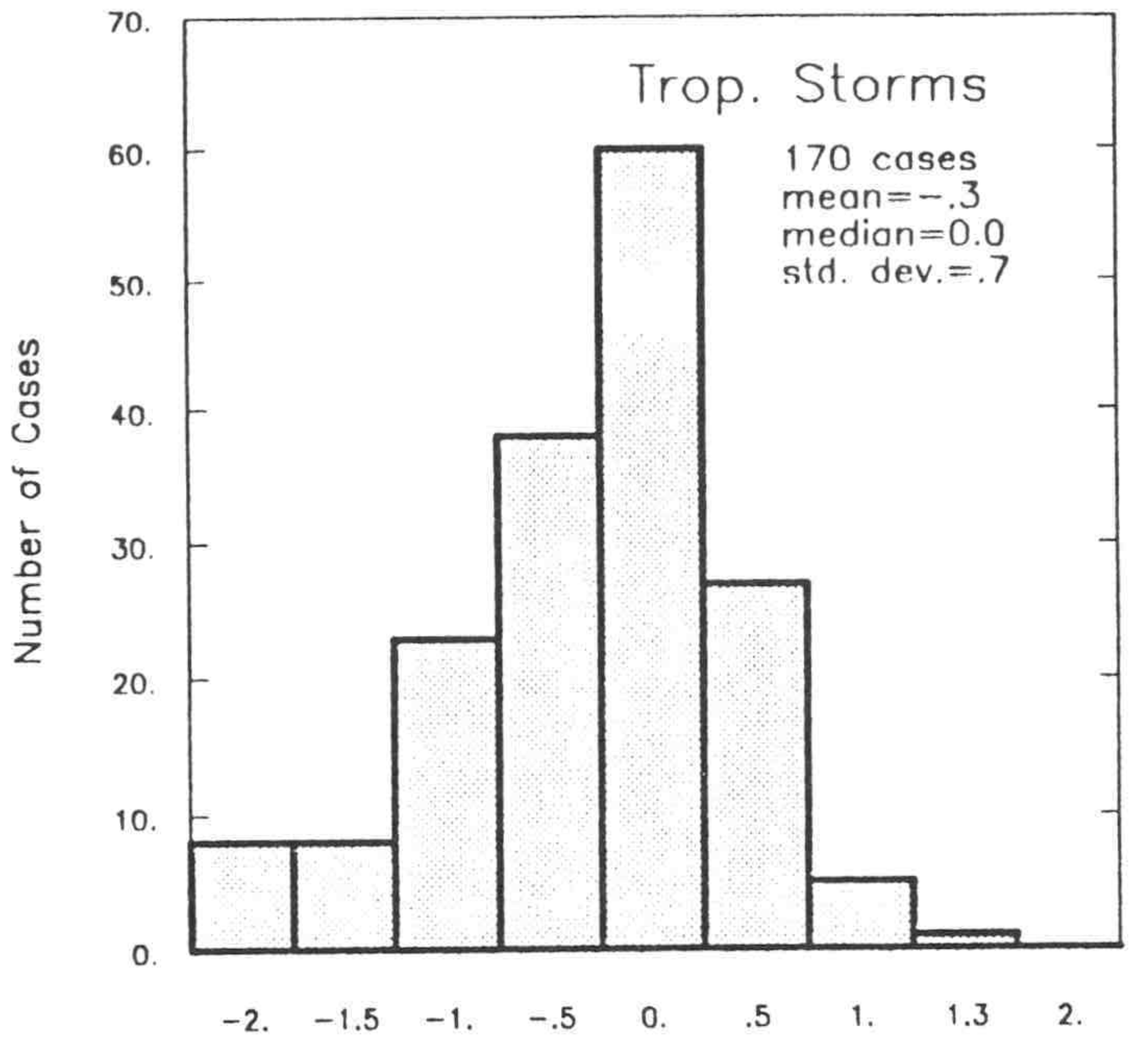


Figure 1-59. Intensity estimate differences (Current Intensity Number for AFGWC versus the NHC. This sample is for tropical storms for the 1986 Eastern Pacific hurricane season.

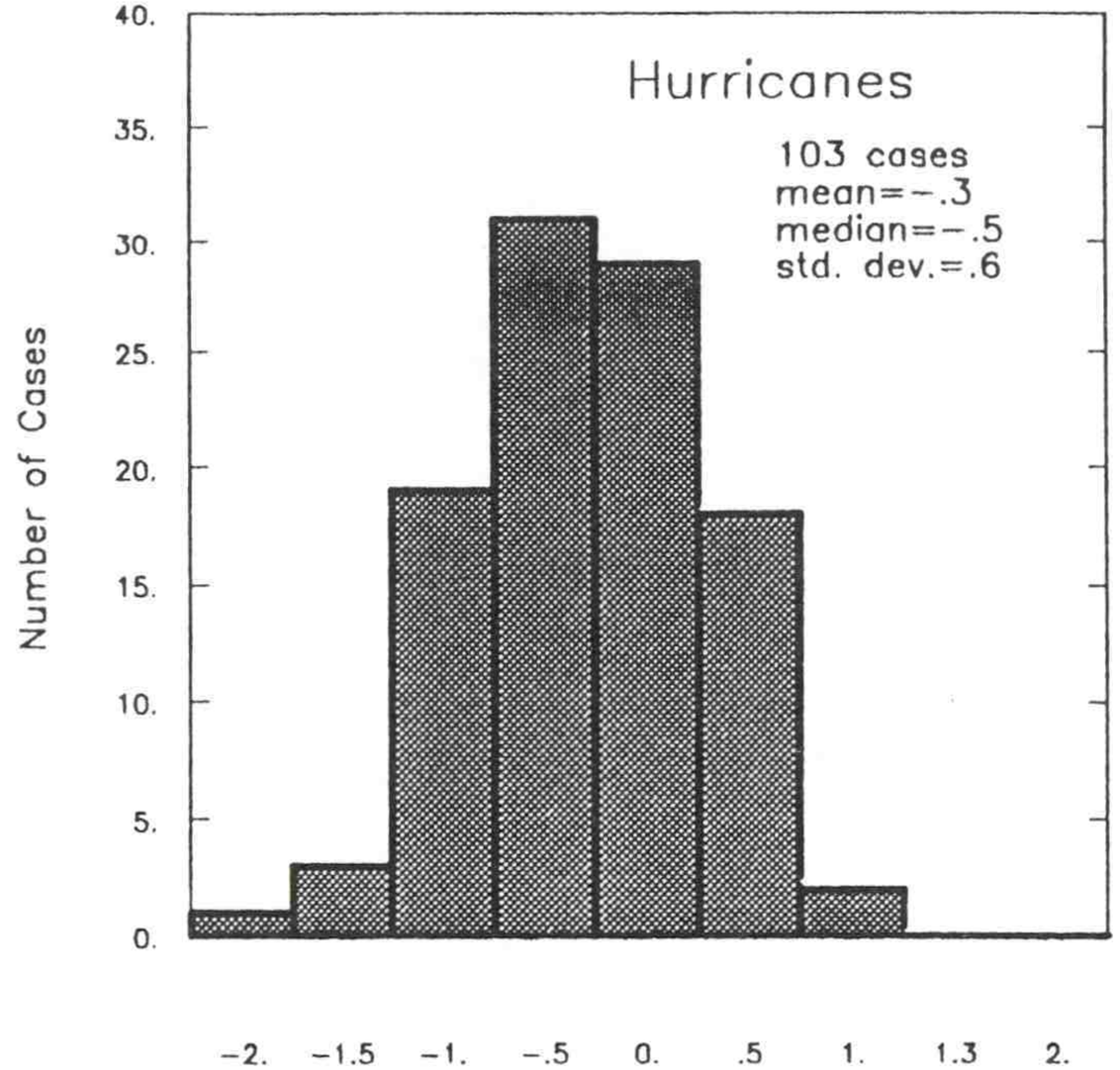


Figure 1-60. Intensity estimate differences (Current Intensity Number) for AFGWC versus the NHC. This sample is for hurricanes for the 1986 Eastern Pacific hurricane season.

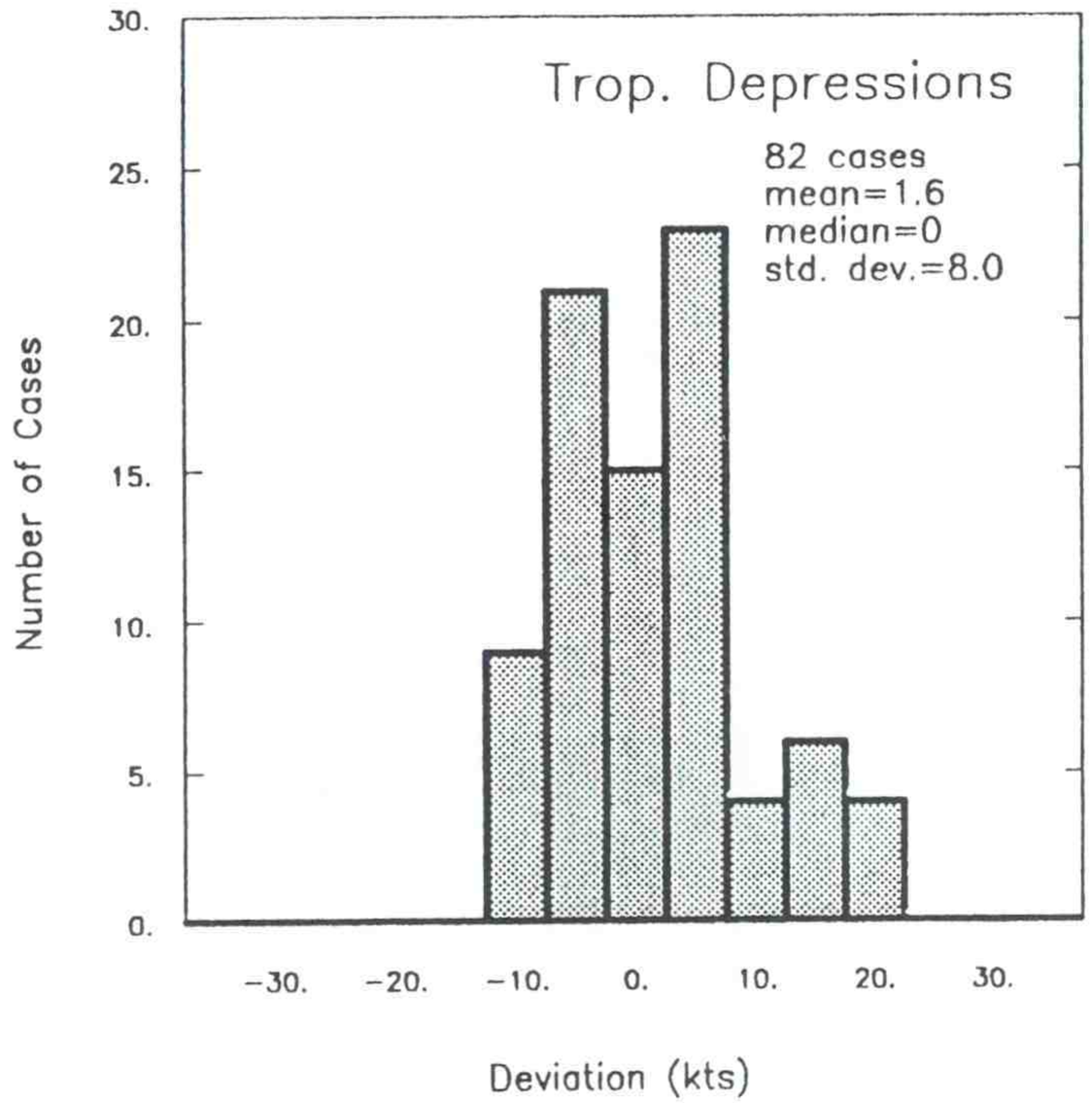


Figure 1-61. Intensity estimate differences (knots) for the AFGWC-determined estimates versus "best track" values. Sample is for tropical depressions for the 1981-86 Atlantic Basin hurricane season.

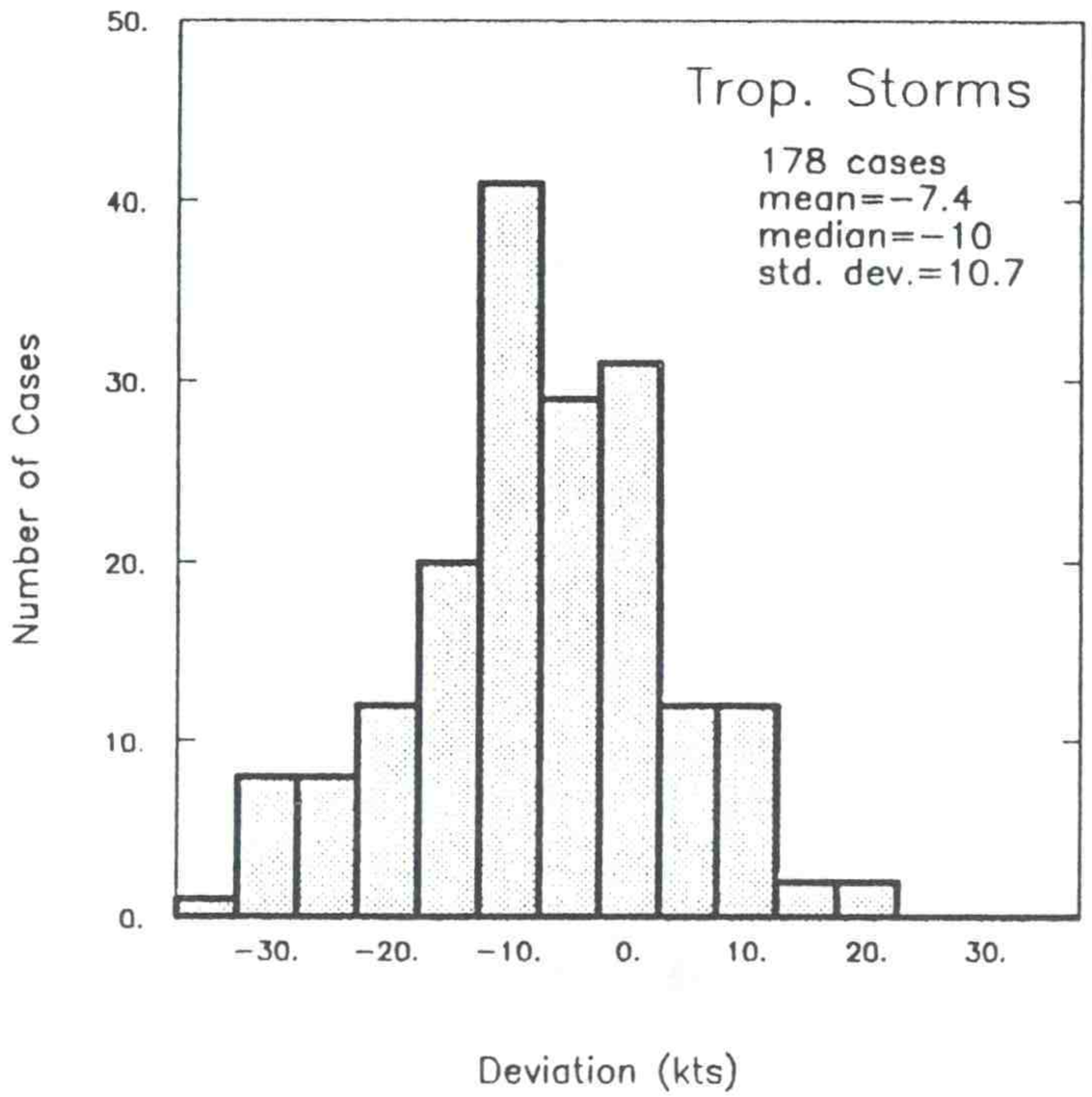


Figure 1-62. Intensity estimate differences (knots) for the AFGWC-determined estimates versus "best track" values. Sample is for tropical storms for the 1981-86 Atlantic Basin hurricane season.

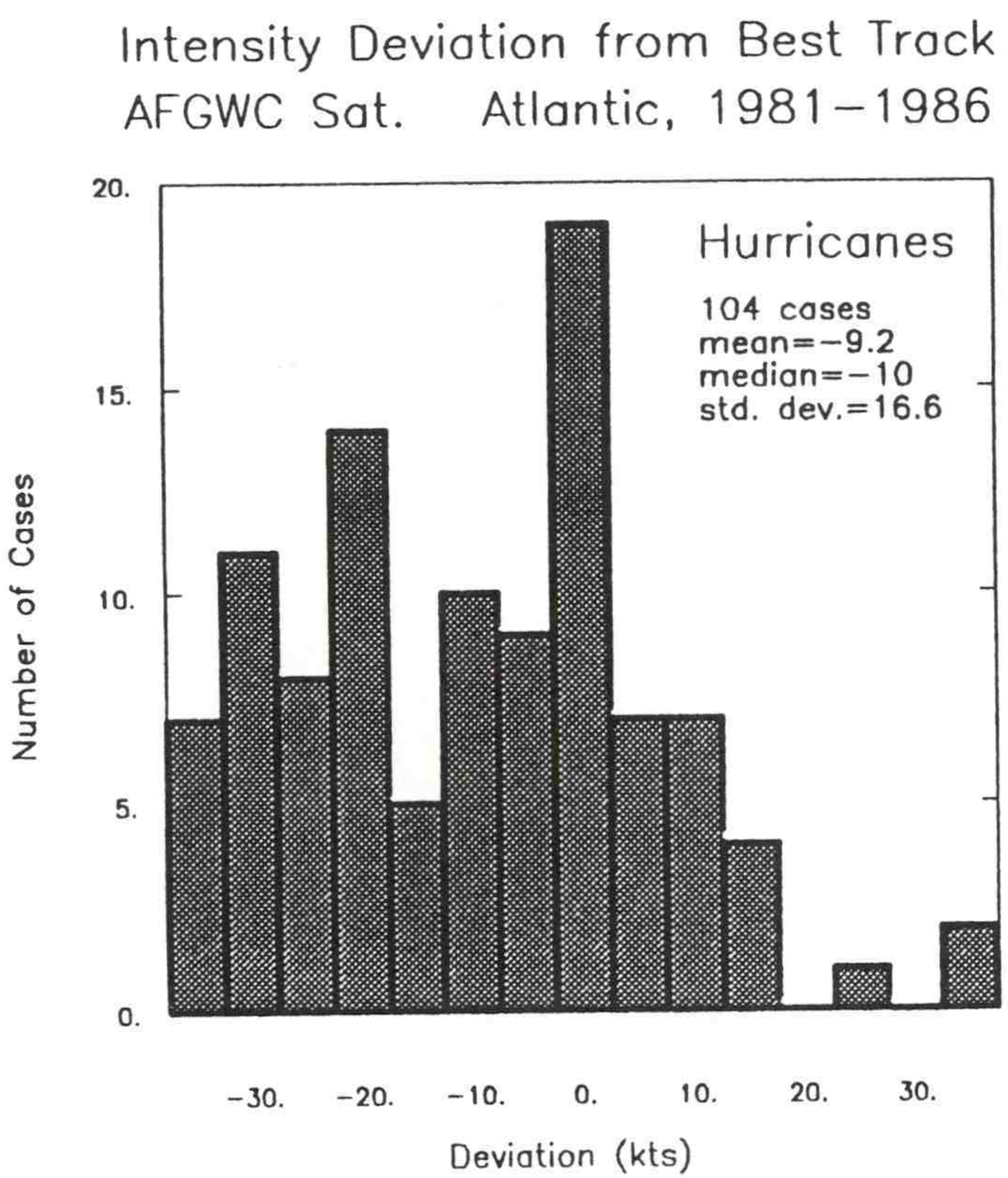


Figure 1-63. Intensity estimate differences (knots) for the AFGWC-determined estimates versus "best track" values. Sample is for hurricanes for the 1981-86 Atlantic Basin hurricane season.

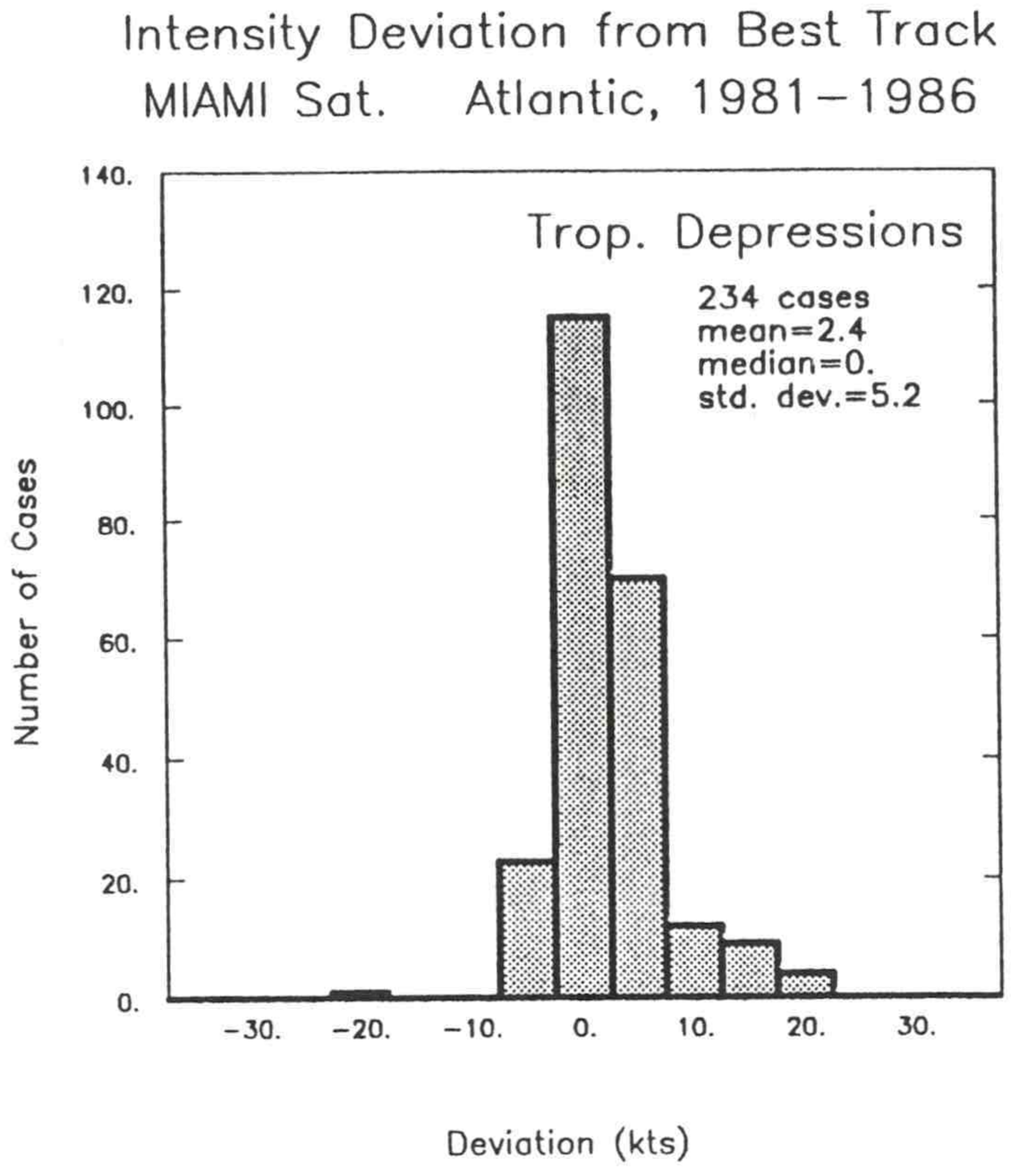


Figure 1-64. Intensity estimate differences (knots) for the NHC-determined estimates versus "best track" values. Sample is for tropical depressions for the 1981-86 Atlantic Basin hurricane season.

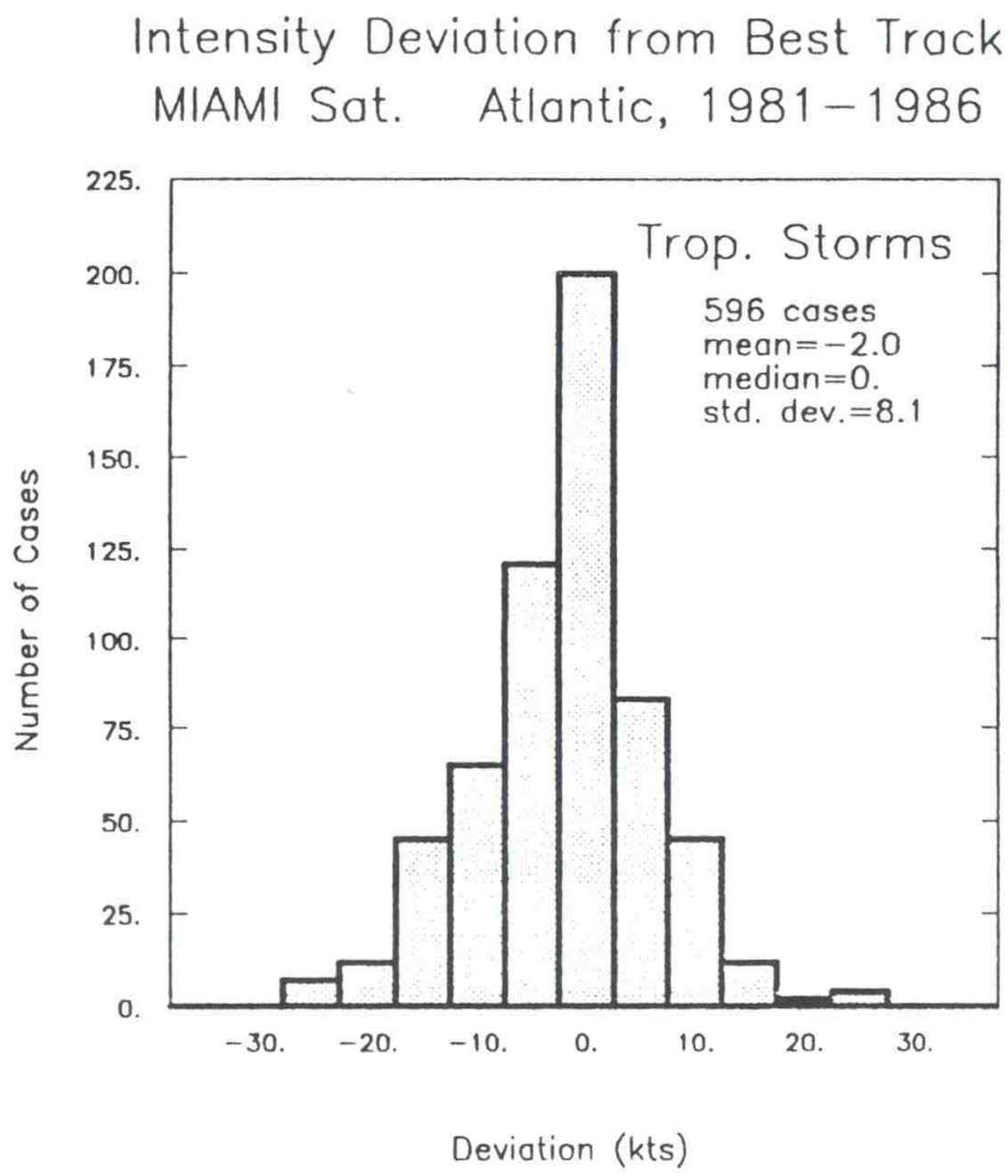


Figure 1-65. Intensity estimate differences (knots) for the NHC-determined estimates versus "best track" values. Sample is for tropical storms for the 1981-86 Atlantic Basin hurricane season.

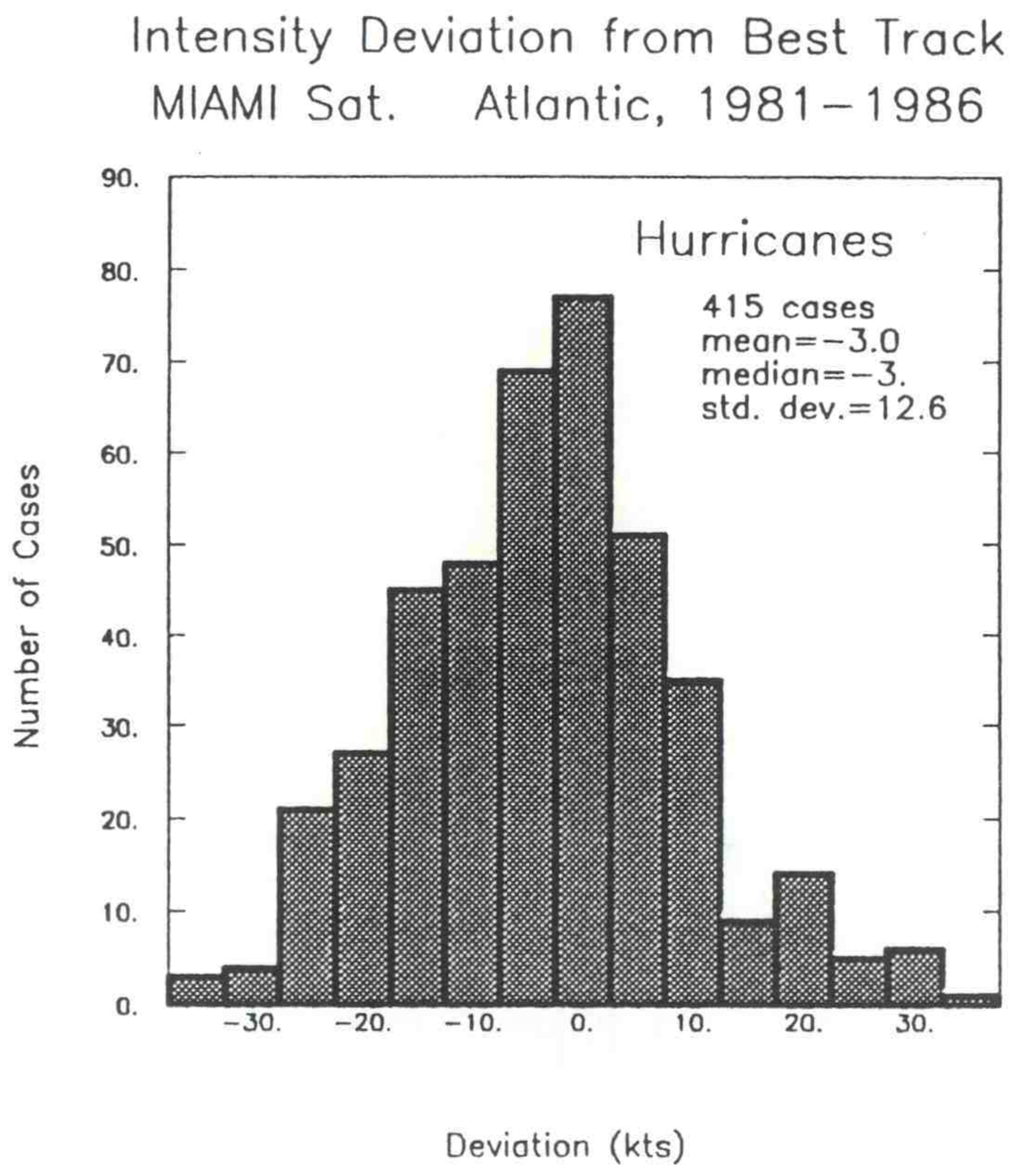


Figure 1-66. Intensity estimate differences (knots) for the NHC-determined estimates versus "best track" values. Sample is for hurricanes for the 1981-86 Atlantic Basin hurricane season.

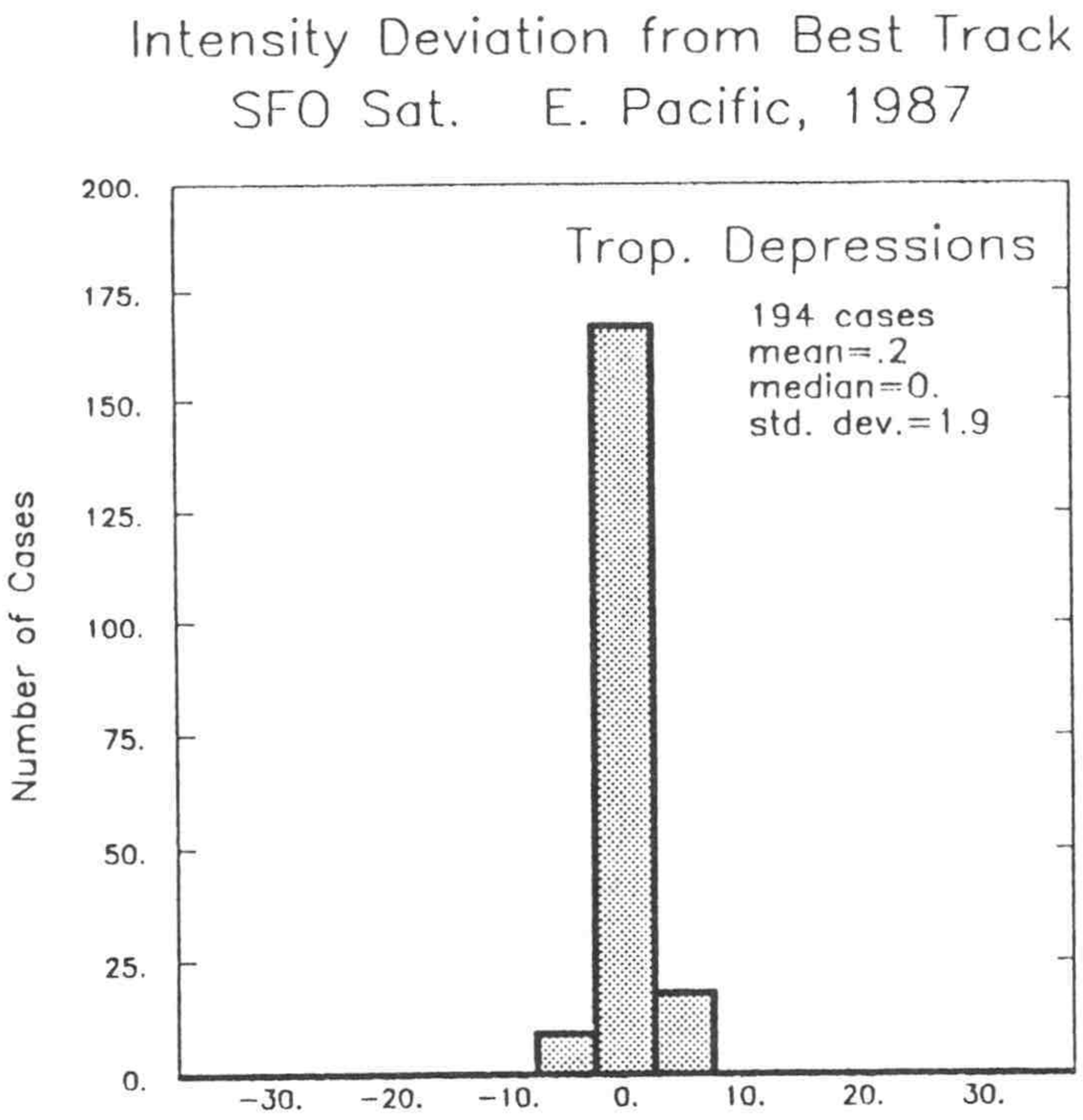


Figure 1-67. Intensity estimate differences (knots) for the EPHC-determined estimates versus "best track" values. Sample is for tropical depressions for the 1987 Eastern Pacific hurricane season.

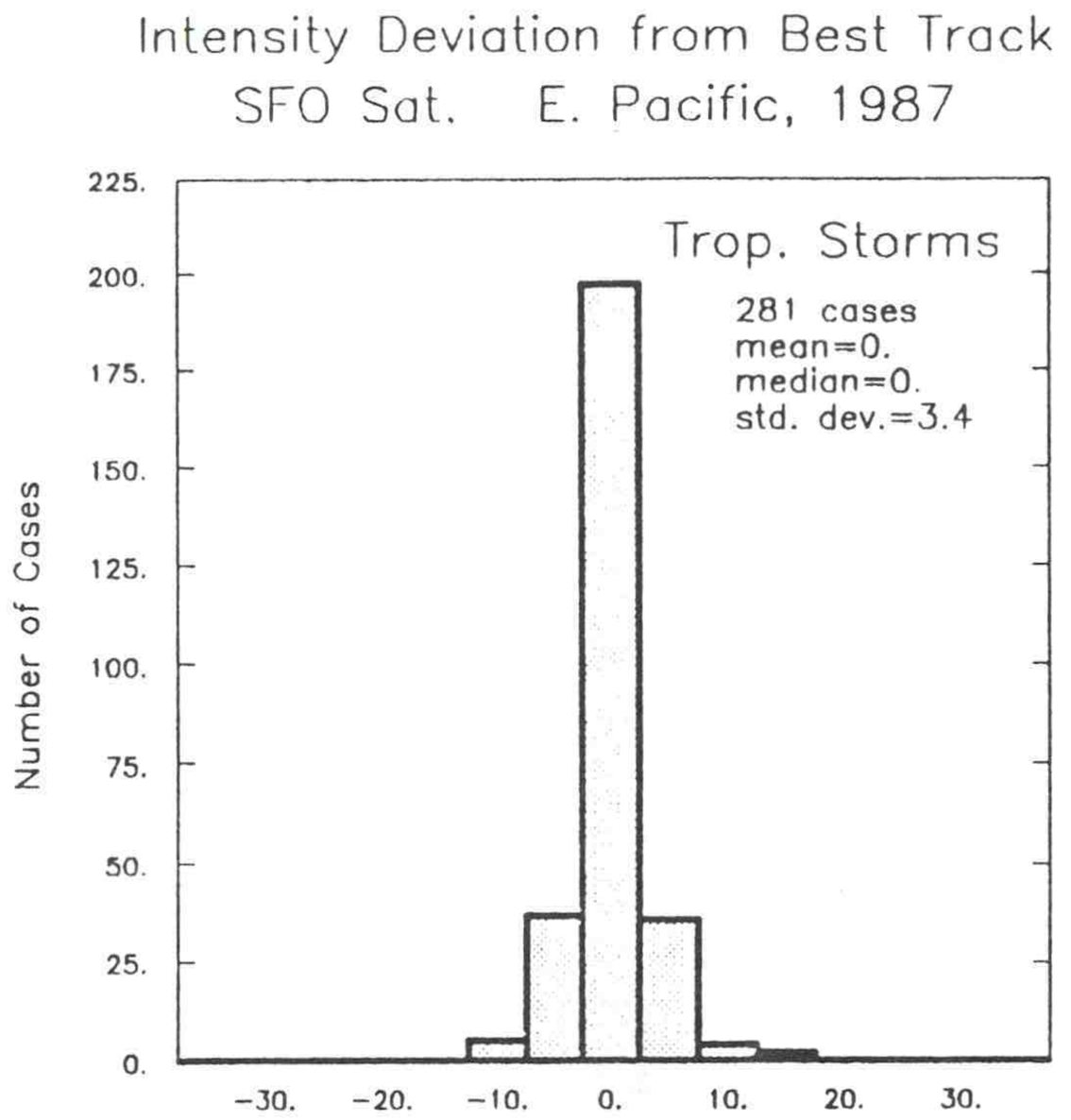


Figure 1-68. Intensity estimate differences (knots) for the EPHC-determined estimates versus "best track" values. Sample is for tropical storms for the 1987 Eastern Pacific hurricane season.

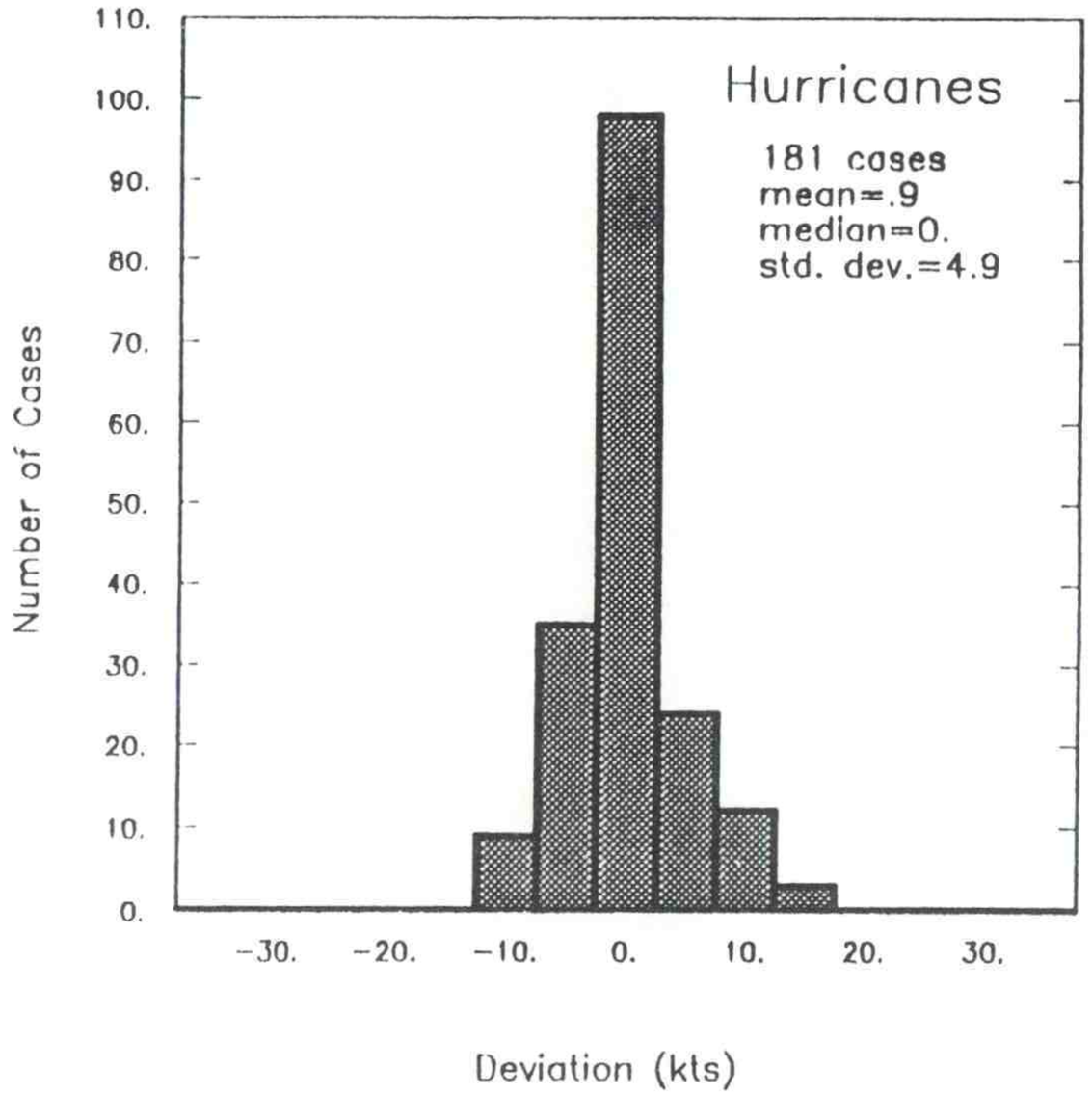


Figure 1-69. Intensity estimate differences (knots) for the EPHC-determined estimates versus "best track" values. Sample is for hurricanes for the 1987 Eastern Pacific hurricane season.

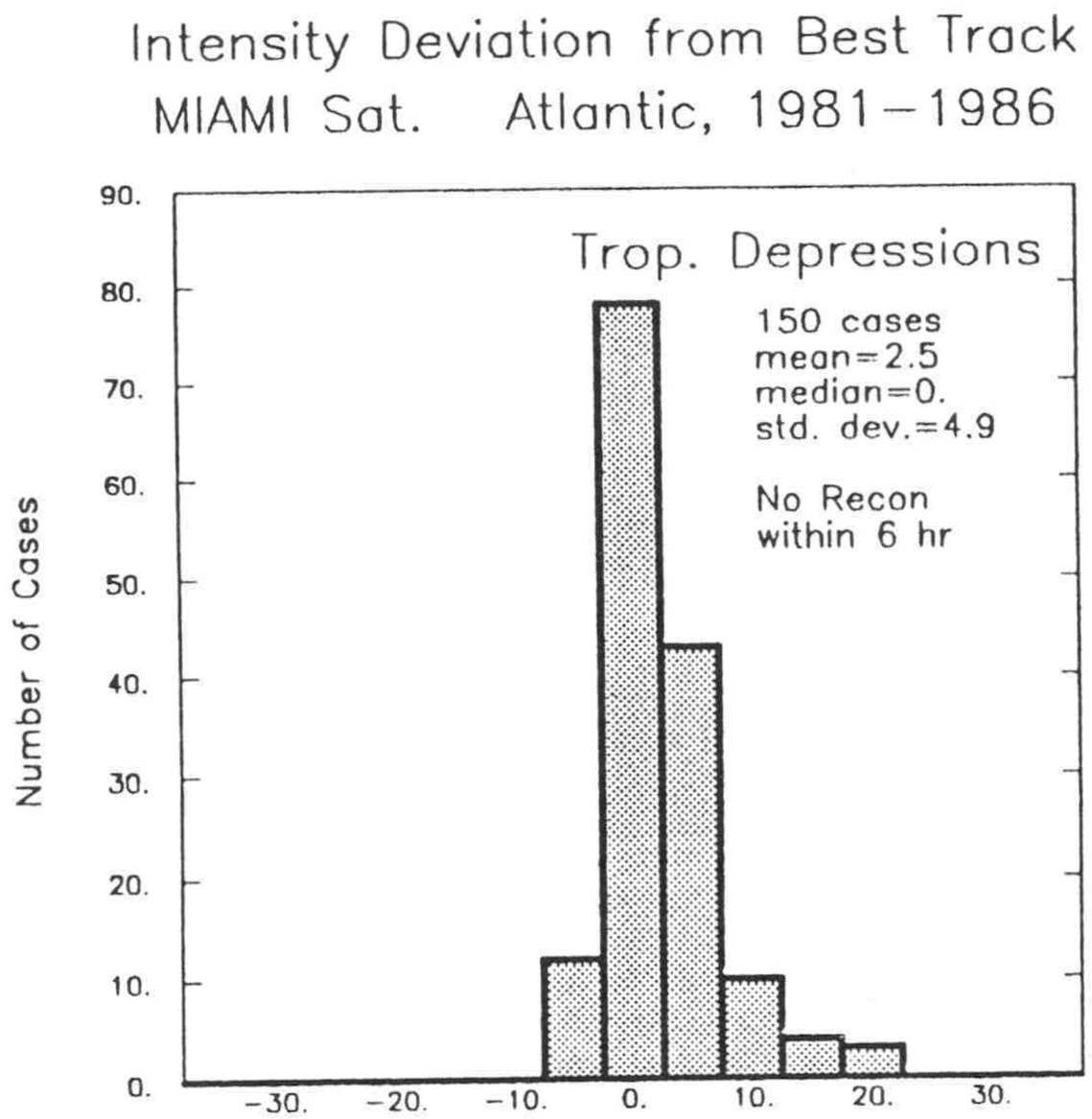


Figure 1-70. Intensity estimate differences (knots) for NHC-determined estimates versus "best track" values. Sample is for tropical depressions for the 1981-86 hurricane season with no aircraft reconnaissance data available within 6 hours of image time.

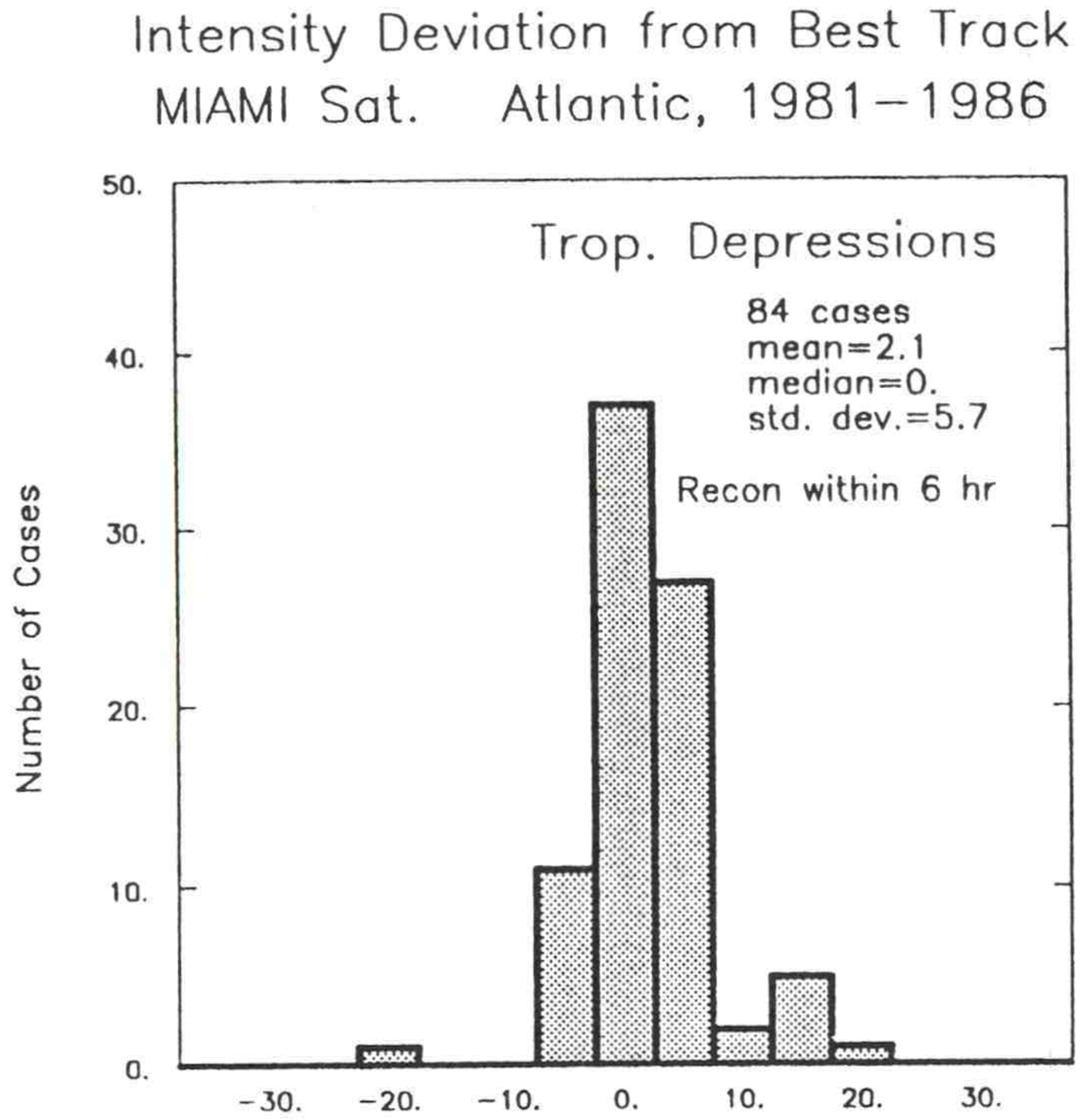


Figure 1-71. Intensity estimate differences (knots) for NHC-determined estimates versus "best track" values. Sample is for tropical depressions for the 1981-86 hurricane season with aircraft reconnaissance data available within 6 hours of image time.

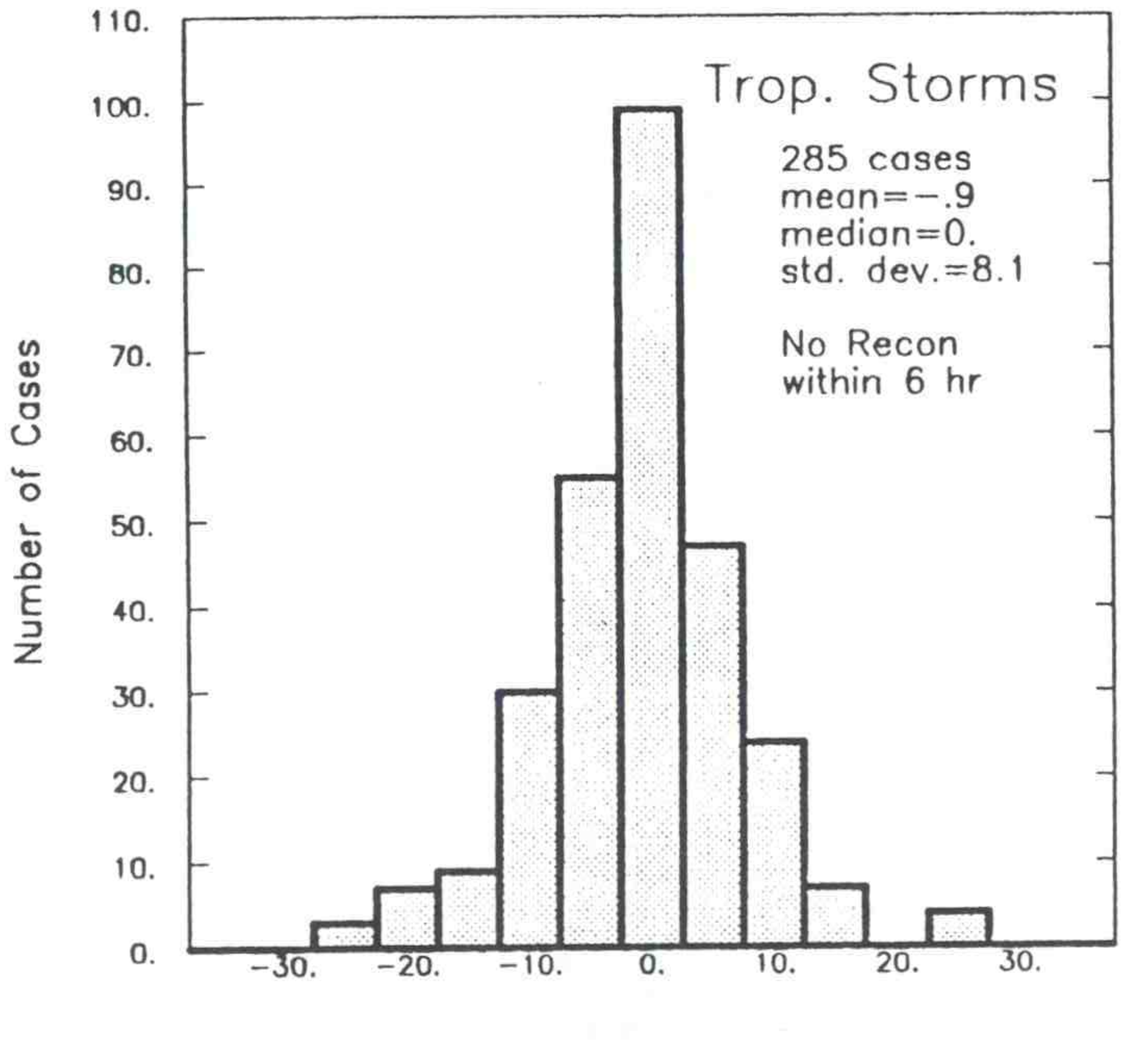


Figure 1-72. Intensity estimate differences (knots) for NHC-determined estimates versus "best track" values. Sample is for tropical storms for the 1981-86 hurricane season with no aircraft reconnaissance data available within 6 hours of image time.

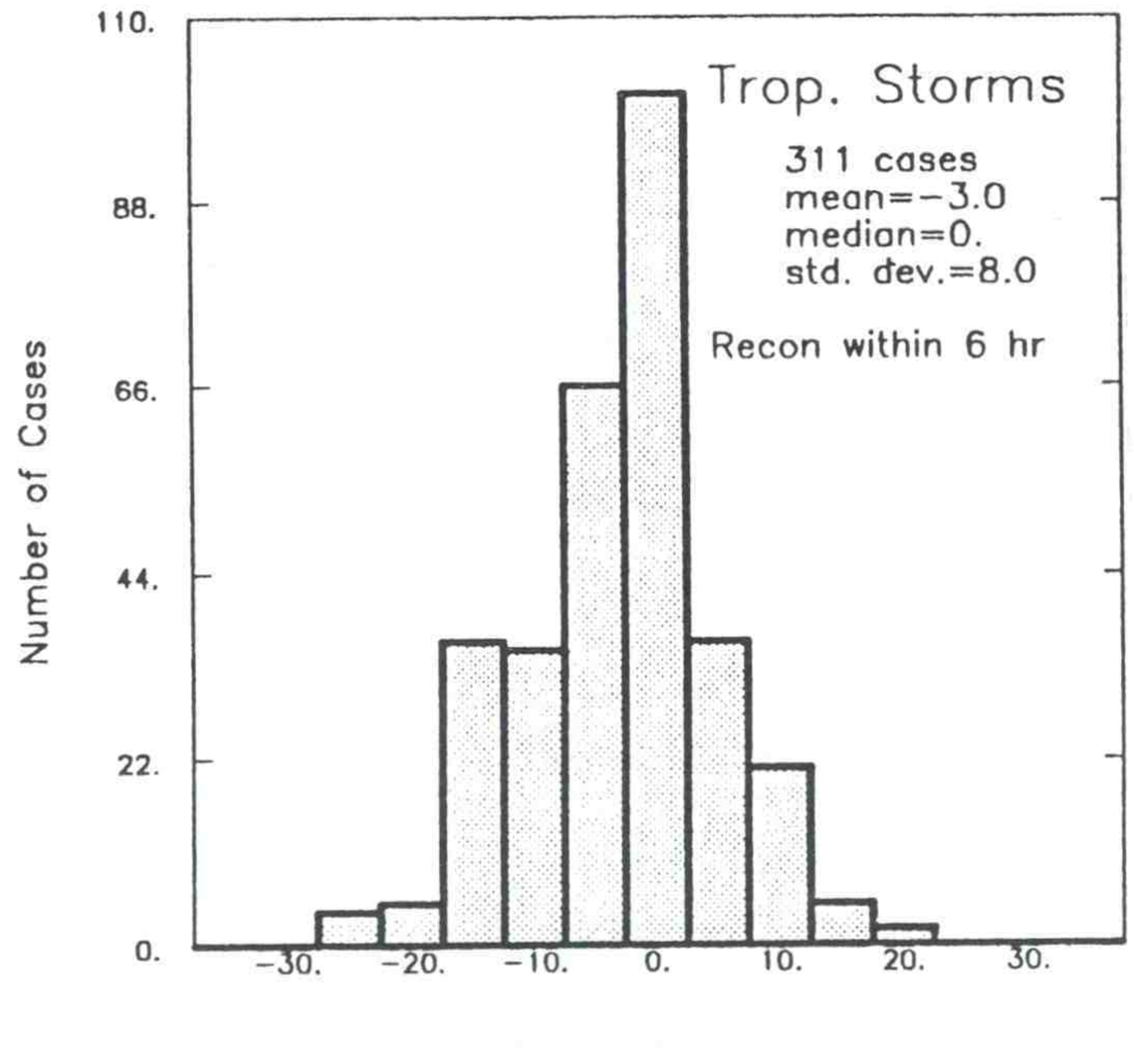


Figure 1-73. Intensity estimate differences (knots) for NHC-determined estimates versus "best track" values. Sample is for tropical storms for the 1981-86 hurricane season with aircraft reconnaissance data available within 6 hours of image time.

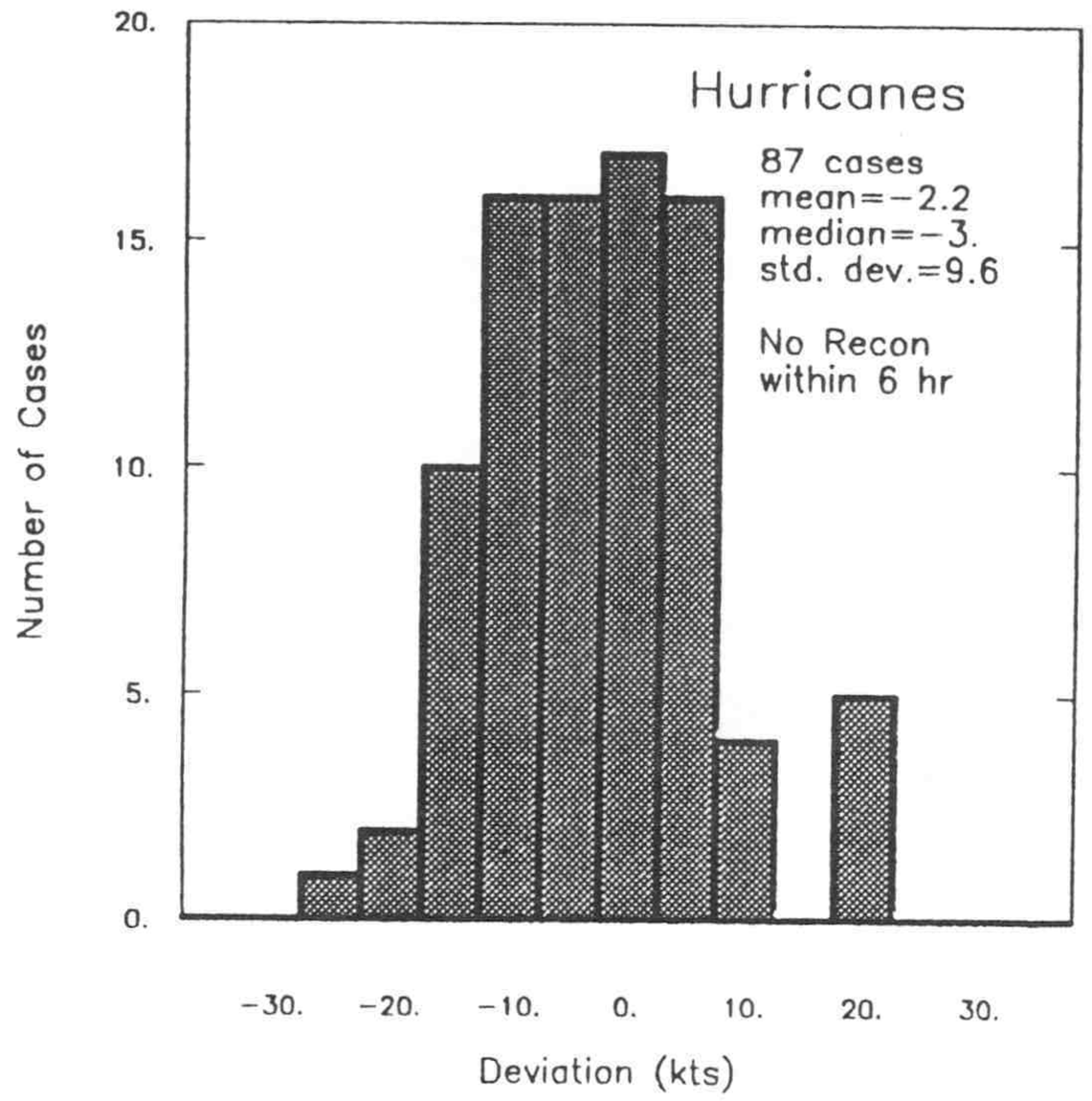


Figure 1-74. Intensity estimate differences (knots) for NHC-determined estimates versus "best track" values. Sample is for hurricanes for the 1981-86 hurricane season with no aircraft reconnaissance data available within 6 hours of image time.

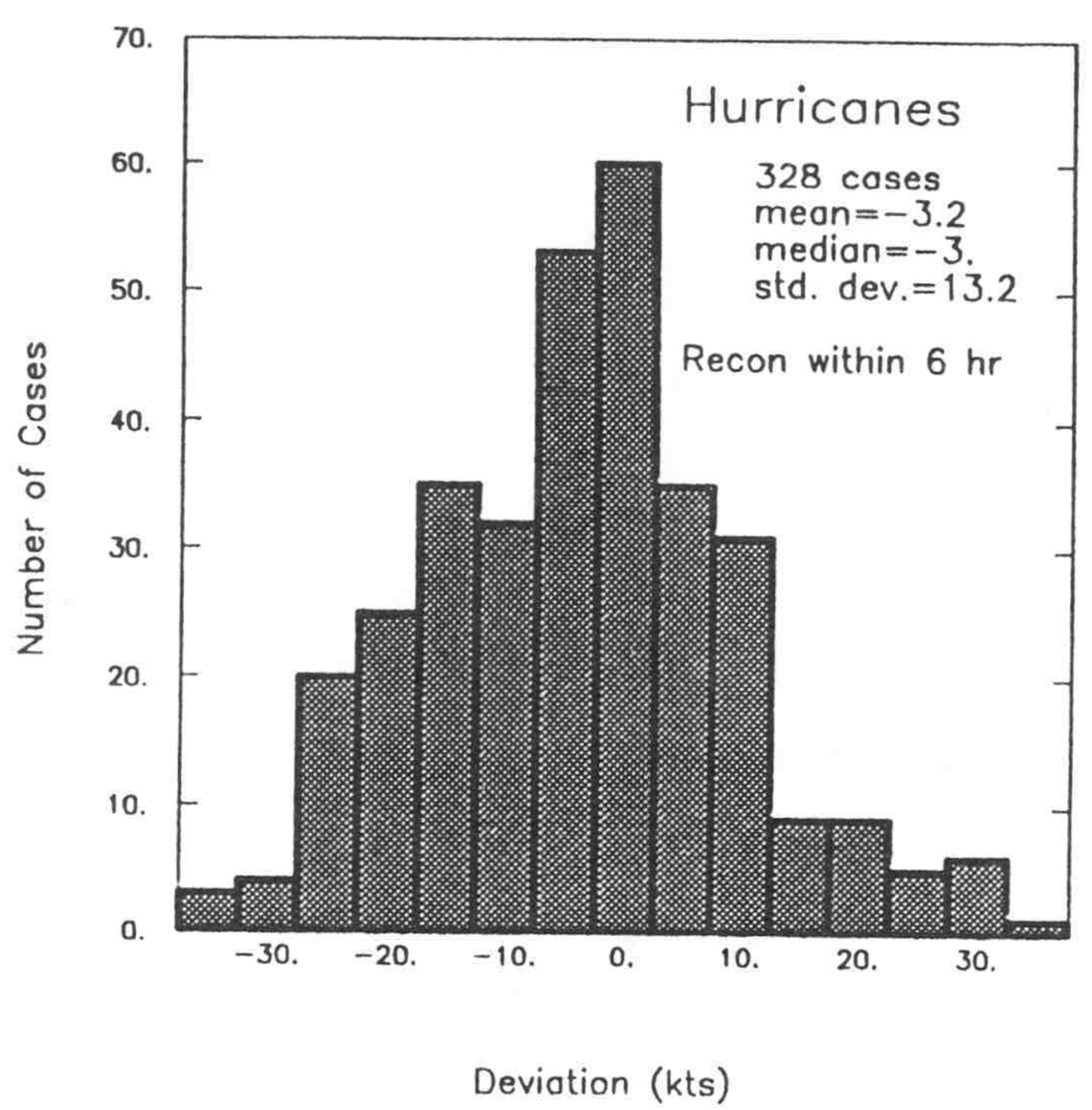


Figure 1-75. Intensity estimate differences (knots) for NHC-determined estimates versus "best track" values. Sample is for hurricanes for the 1981-86 hurricane season with aircraft reconnaissance data available within 6 hours of image time.

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PART 2

A PRELIMINARY EVALUATION OF THE DISPERSION OF TROPICAL CYCLONE POSITION AND INTENSITY ESTIMATES DETERMINED FROM SATELLITE IMAGERY

by

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2.1. Introduction. Tropical cyclone position and intensity estimates have been made from satellite imagery for a number of years. The most established procedure for these estimates is known as the Dvorak technique (Dvorak, 1973). This method has been in operational use in the United States since the early 1970s and has gradually gained acceptance by several other countries with tropical cyclone forecasting responsibilities. The purpose of this study is to provide information on the dispersion of Dvorak tropical cyclone position and intensity estimates about their group mean.

2.2. Background.

2.2.1. Analysts at the National Hurricane Center (NHC) of the National Weather Service[1] (NWS) and the Synoptic Analysis Branch (SAB) of the National Environmental Satellite, Data, and Information Service (NESDIS) have been providing operational "classifications" of tropical cyclones by use of the Dvorak technique since 1971. These classifications include estimating the position of a cloud system center, usually assumed to be a wind circulation center, and estimating the current intensity (C.I.) number for tropical disturbances when the appropriate criteria of the technique are satisfied. Table 2-1 shows the empirical relationship between the C.I. number, maximum wind speed, and minimum sea level pressure.

2.2.2. Portions of earlier studies (Sheets and Grieman (1975), Shewchuck and Weir (1980), and Gaby, et al. (1980), which compared operational satellite classifications with

[1] Formerly at the Miami Satellite Field Services Station of NESDIS.

"best track" data, may not be totally reperesentative for two primary reasons. First, the best track data are determined after the fact using all available data, including the satellite classifications. Thus, the best track data are not independent of the satellite data. Second, the operational satellite classifications may have been, at times, influenced by other sources, such as surface reports, advisories, and aircraft reconnaissance data. In particular, comparisons of estimates with and without aircraft reconnaissance data show that at times the satellite classifications are much worse when no aircraft data are available (Sheets and McAdie, 1988).

Table 2-1. The empirical relationship between the current intensity (C.I.) number, the maximum wind speed (MWS), and the minimum sea-level pressure (MSLP) in tropical cyclones. (Dvorak, 1984)

C.I. Number	MWS (kt)	MSLP (kPa) (Atlantic)	MSLP (kPa) (NW Pacific)
1	25	-	-
1.5	25	-	-
2	30	100.9	100.0
2.5	35	100.5	99.7
3	45	100.0	99.1
3.5	55	99.4	98.4
4	65	98.7	97.6
4.5	77	97.9	96.6
5	90	97.0	95.4
5.5	102	96.0	94.1
6	115	94.8	92.7
6.5	127	93.5	91.4
7	140	92.1	89.8
7.5	155	90.6	87.9
8	170	89.0	85.8

2.2.3. Some earlier studies of satellite classifications were made before the routine use of enhanced infrared imagery. The enhanced infrared imagery has made application of the Dvorak technique simpler and more objective than when only visible and/or unenhanced infrared imagery are available. See Figure 2-1 for an example of visible, unenhanced infrared and enchanced infrared imagery. The BD enhancement shown in this example was developed specifically

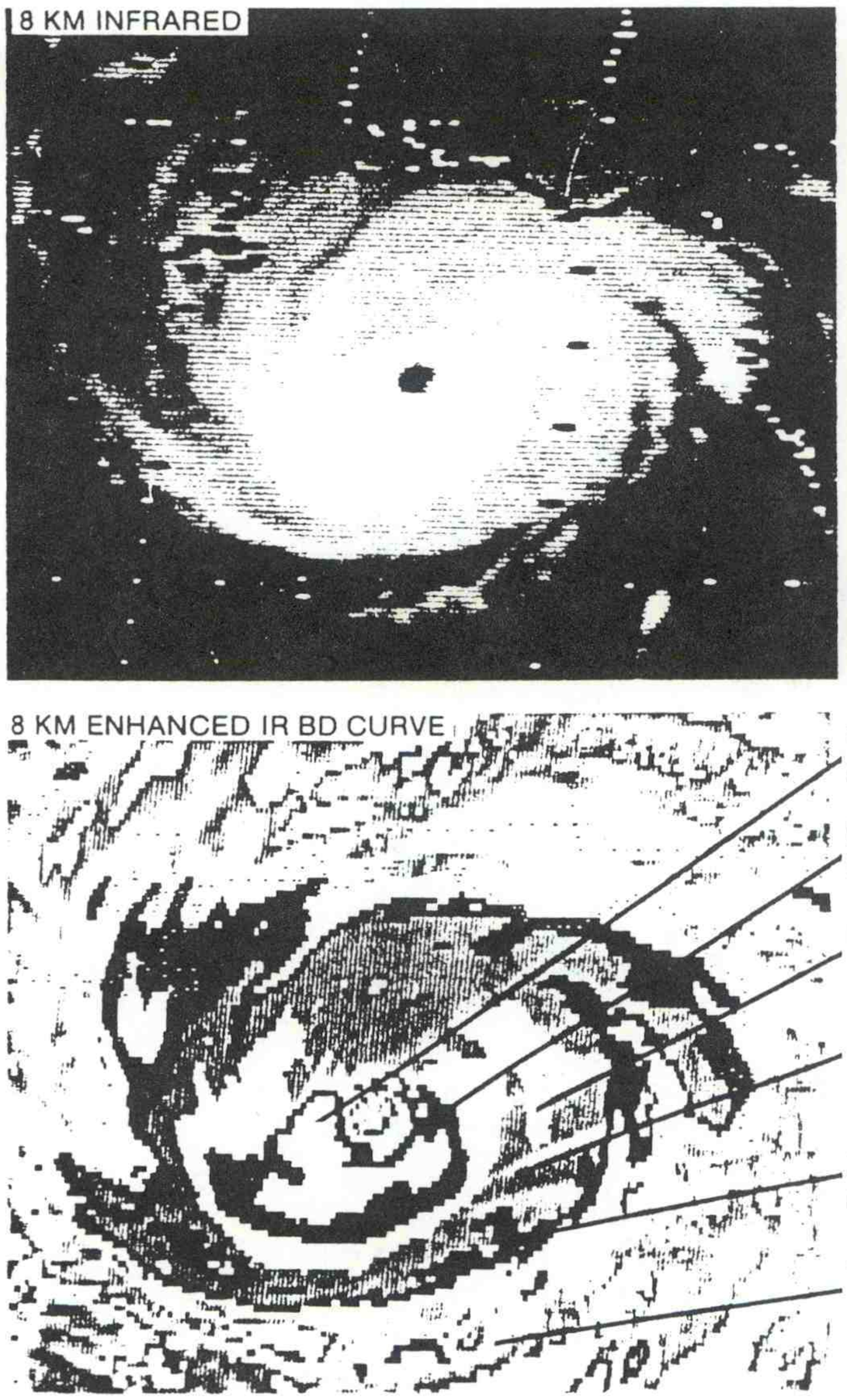


Figure 2-1. Example of visible, unenhanced infrared, and enhanced infrared imagery (from Dvorak).

for tropical cyclone classifications and is used in the current version of the Dvorak technique.

2.2.4. For tnese reasons, this study uses currently available satellite imagery including enhanced infrared imagery and concentrates on the dispersion or scatter of the satellite classifications themselves, without comparisons to dependent best track data and without contamination from other sources.

2.3. Data and Methodology.

2.3.1. GOES-6 imagery was selected for fourteen tropical cyclones in the Eastern North Pacific during 1985. Officially, nine of these cyclones reached hurricane strength while the remaining five reached only tropical storm strength. Seven analysts from the NHC and seven analysts from the SAB were given operationally obtained facsimile pictures typical of imagery currently available from the GOES distribution system. Each of the fourteen analysts was asked to estimate the position and intensity of the tropical cyclones at 6-hr intervals. Classifications were primarily made from enchanced infrared pictures of 4 km geographical coverage (7-km resolution) with the BD enhancement, at 0130, 0730, 1330, and 1930 UTC. When available, 4-km resolution visible pictures were included near 0000 and 1800 UTC, although classifications were not required at these times. Each analyst started with the first picture available for a disturbance. The analyst classified according to the procedures of the Dvorak technique, one picture at a time, without knowledge of other pictures. Only after each classification was made could the next available picture be examined. The analyst was not permitted to change past classifications based upon later pictures but retained past photographs. A total of 5,328 classifications were made in a non-operational mode, with no other information supplied to the analyst.

2.3.2. To calculate statistics on the dispersion of the position estimates, the centroid (average latitude and average longitude) of all position estimates for a given cyclone and time was first calculated. Next, individual deviations between each analyst's classification position and the centroid for the given cyclone and time were determined. Thus, a maximum of fourteen individual position deviations exist for each classification time.

2.3.3. To calculate statistics on the dispersion of the intensity estimates, the average wind speed of all intensity

estimates for a given cyclone and time was first calculated. Next, individual deviations between each analyst's classification wind speed and group average wind speed for the given cyclone and time were determined. Thus, a maximum of fourteen individual intensity deviations exist for each classification time.

2.3.4. Statistics on the dispersion of position estimates and intensity estimates were calculated for the tropical depression and weaker stage, for the tropical storm stage, for category 1 and 2 hurricane stages, and for the category 3 and greater hurricane stages. Categories are defined by the Saffir-Simpson Hurricane Scale (Simpson, 1974) (see Appendix C) with the higher categories--3 and above--being classified as major hurricanes. Some non-depression disturbances are included since the weakest classifications of the Dvorak technique do not necessarily imply a surface circulation. For this study, the intensity stage of tropical depression, tropical storm, and category of hurricane was defined by the group average wind speed of all intensity estimates for a given cyclone and time.

2.4. Results of Cyclone Position Estimates.

2.4.1. Figure 2-2 depicts the deviations of the individual satellite-determined positions from the centroid of all position estimates for the tropical depression stage and weaker systems. The figure bars represent values at 5 nmi intervals where the first bar represents values of 0 to 4 nmi, the second bar is 5 to 9 nmi, etc., and the last bar represents values 100 nmi or greater. Note the large mean and standard deviation for this weak stage of development. In fact, 50 percent of the cases differ by more than 25 nmi, and 10 percent of the cases differ by more than 62 nmi, as shown in Table 2-2.

2.4.2. Figure 2-3 resembles Figure 2-2 except it is the tropical storm stage. As expected, the mean and standard deviation are less than for the weaker stage of development. However, 50 percent of the cases differ by more than 18 nmi, and 10 percent of the cases differ by more than 48 nmi.

2.4.3. Figure 2-4 shows the position deviations for the category 1 and 2 hurricane stages. The trend toward a lower mean and standard deviation continues. However, 10 percent of the cases differ by more than 30 nmi, even for this strong stage of development.

2.4.4. Figure 2-5 shows the position deviation for the category 3 and greater hurricane stages. The mean and

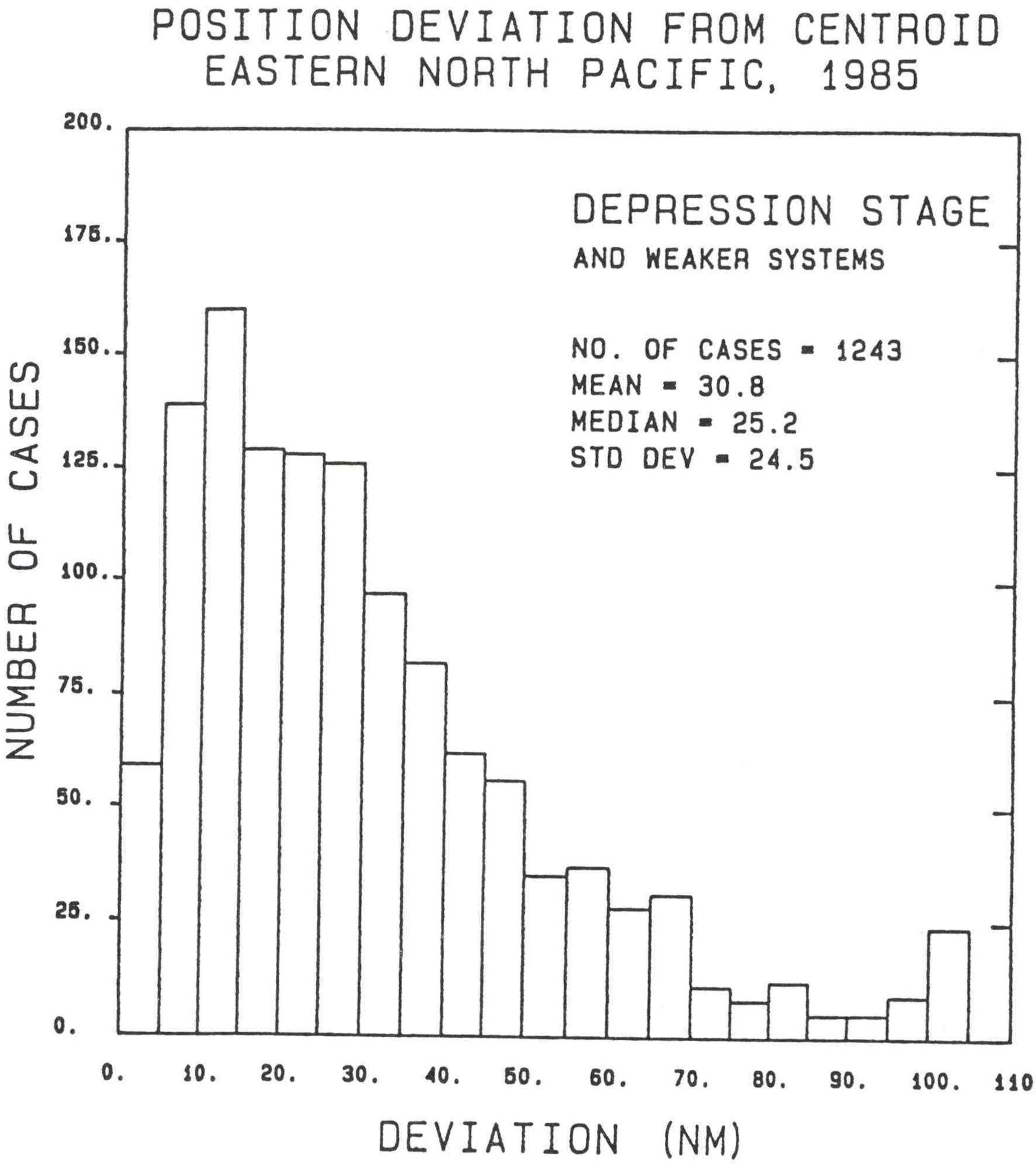


Figure 2-2. Deviations (nmi) of individual satellite-determined position estimates from the centroid for the tropical depression stage and weaker systems.

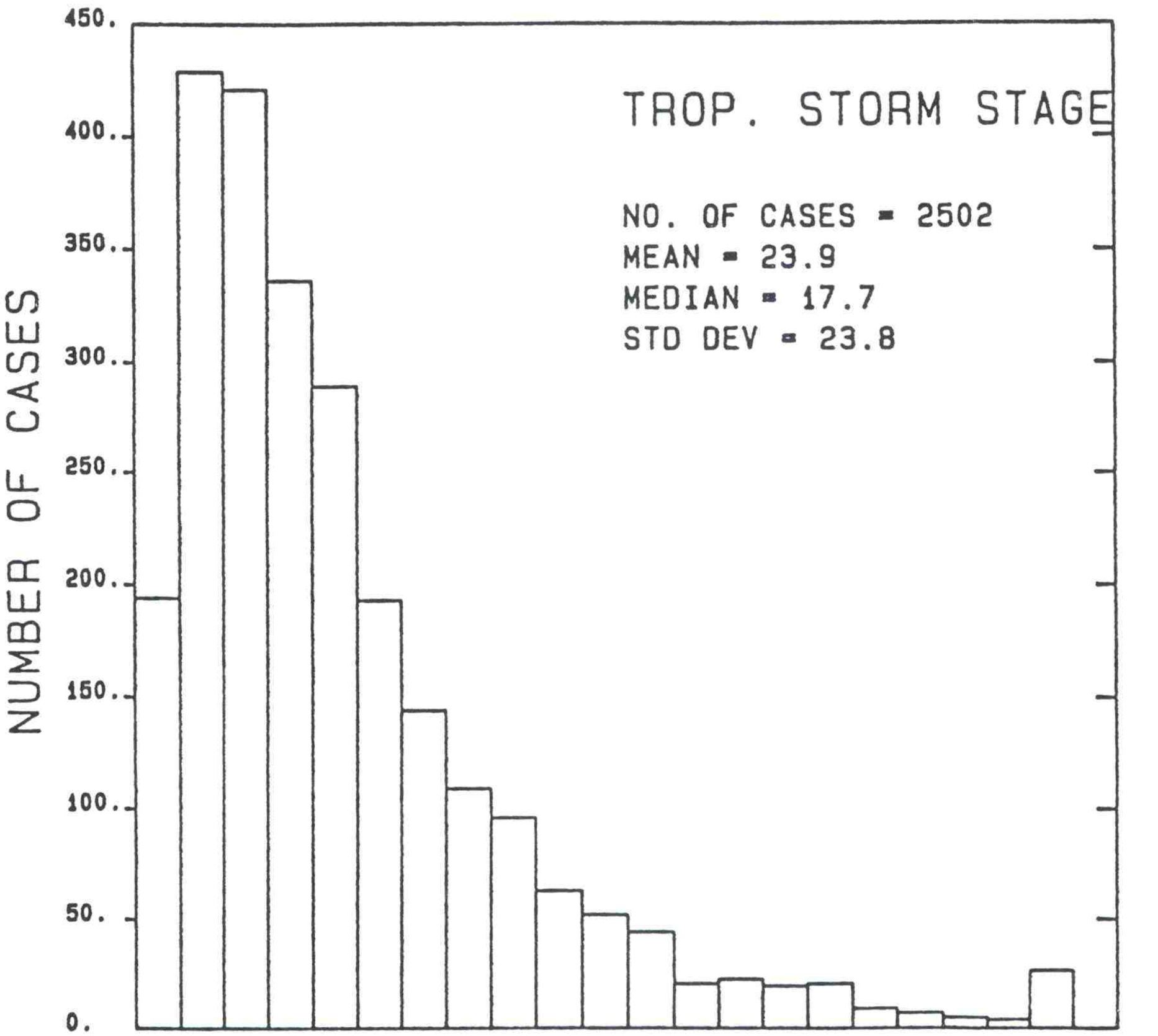


Figure 2-3. Deviations (nmi) of individual satellite-determined position estimates from the centroid for the tropical storm stage.

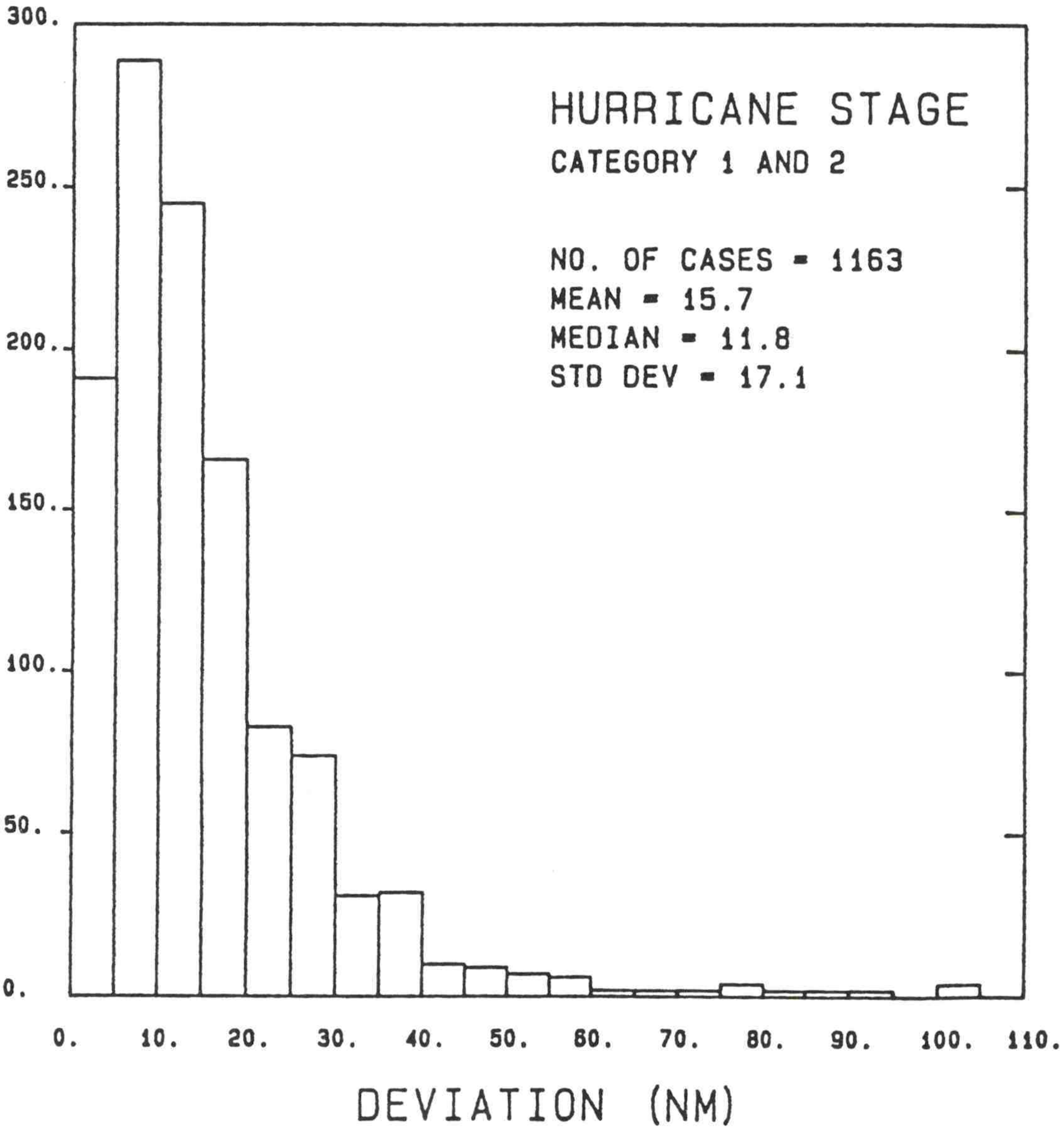


Figure 2-4. Deviations (nmi) of individual satellite-determined position estimates from the centroid for the category 1 and 2 hurricane stage.

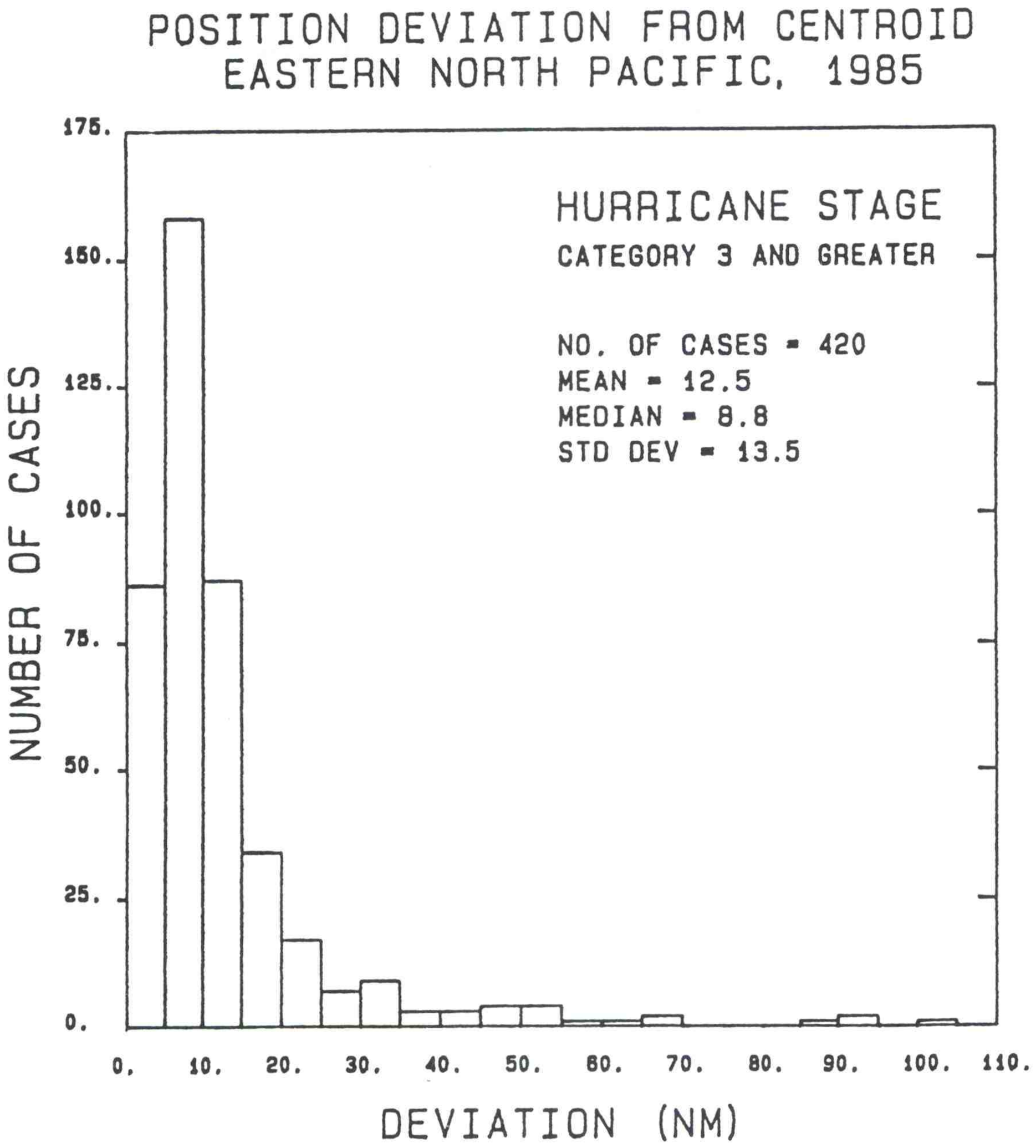


Figure 2-5. Deviations (nmi) of individual satellite-determined position estimates from the centroid for the category 3 and greater hurricane stage.

standard deviation are low, as expected. For this stage of development, 10 percent of the cases differ by more than 24 nmi.

Table 2-2. Deviations (in nmi) of satellite determined positions from the centroid. The 50% median and 10% columns indicate deviation values exceeded by 50 percent and 10 percent of the cases, respectively.

Stage	No. of Cases	Mean	Std.Dev.	50%	10%
Trop. depression and weaker	1243	31	25	25	62
Tropical Storm	2502	24	24	18	48
Hurricane Category 1 & 2	1163	16	17	12	30
Hurricane Category 3 +	420	12	14	9	24

The four categories of tropical cyclone intensity used are defined by the group average of maximum wind estimates, W, lying within the following ranges:

Depression and weaker: $W < 34$ kt
Tropical storm: $34 \leq W < 64$ kt
Category 1 or 2 hurricane: $64 \leq W < 96.4$ kt
Category 3 or greater hurricane: $W \geq 96.4$ kt

2.4.5. It should be emphasized that it is impossible to determine the relationship between the centroid and the actual cyclone position in the absence of any absolute ground truth.

2.5. Results of Cyclone Intensity Estimates. Figures 2-6 through 2-9 depict deviations of individual intensity estimates from the group average wind speed. Just as it is impossible to determine the relationship between the centroid and the actual cyclone position, it is also impossible to determine the relationship between the group average wind speed and the actual wind speed in the absence of any absolute ground truth. By definition, the mean of the intensity deviations will be zero. The deviations are displayed by the figures in terms of wind speed in knots at 5-kt intervals with bar graphs centered on even 5-kt values.

2.5.1. Figure 2-6 shows very limited dispersion for the depression stage and weaker systems. This is expected, since the only possible wind speed estimates in the Dvorak technique less than tropical storm strength are 25 and 30 kt.

2.5.2. Figure 2-7 shows greater scatter for the tropical storm stage, with approximately 5 percent of the cases differing from the group average by more than 15 kt. A small number of differences of more that 25 kt are noted.

2.5.3. Figures 2-8 and 2-9 show even greater scatter for the hurricane stages. In the category 3 and greater hurricane stage, approximately 5 percent of the cases differ from the group average by more than 20 kt.

2.6. Summary and Conclusions. This study has produced large-sample statistics on the dispersion of tropical cyclone position and intensity estimates manually determined from satellite imagery. The emphasis has been on obtaining a measure of the internal consistency of these estimates, and does not address the question of absolute accuracy.

2.6.1. As expected, the deviations of the satellite-determined positions from the centroid positions were largest for weaker systems and decreased as the tropical cyclone intensity increased,. However, large deviations were still noted for some tropical storms and hurricanes. In fact, 10 percent of the cases differed by more than 48 nmi for the tropical storm stage, and 10 percent of the cases differed by more than 30 nmi for the hurricane category 1 and 2 stage. These large differences could obviously have major impacts on tropical cyclone forecasts and warnings.

2.6.2. Satellite-determined intensity deviations from the group average wind speeds were, in general, small. This internal consistency of the intensity estimates is a credit to the improvements in the Dvorak technique. In this study, large deviations of 25 kt or more were only occasionally noted. Other studies (Sheets and McAdie, 1988), in which analysts used different sources of satellite data, indicated larger deviations. In addition, the Sheets and McAdie evaluations of satellite-determined intensity deviations from the best track indicated larger deviations, with the possibility of a category 3 hurricane existing when only a category 1 hurricane was estimated by satellite. Considering the difference in damage potential between a category 1 and category 3 hurricane, the possibility of such a large misinterpretation should not be ignored by decisionmakers using satellite data as a single source for cyclone intensity estimates.

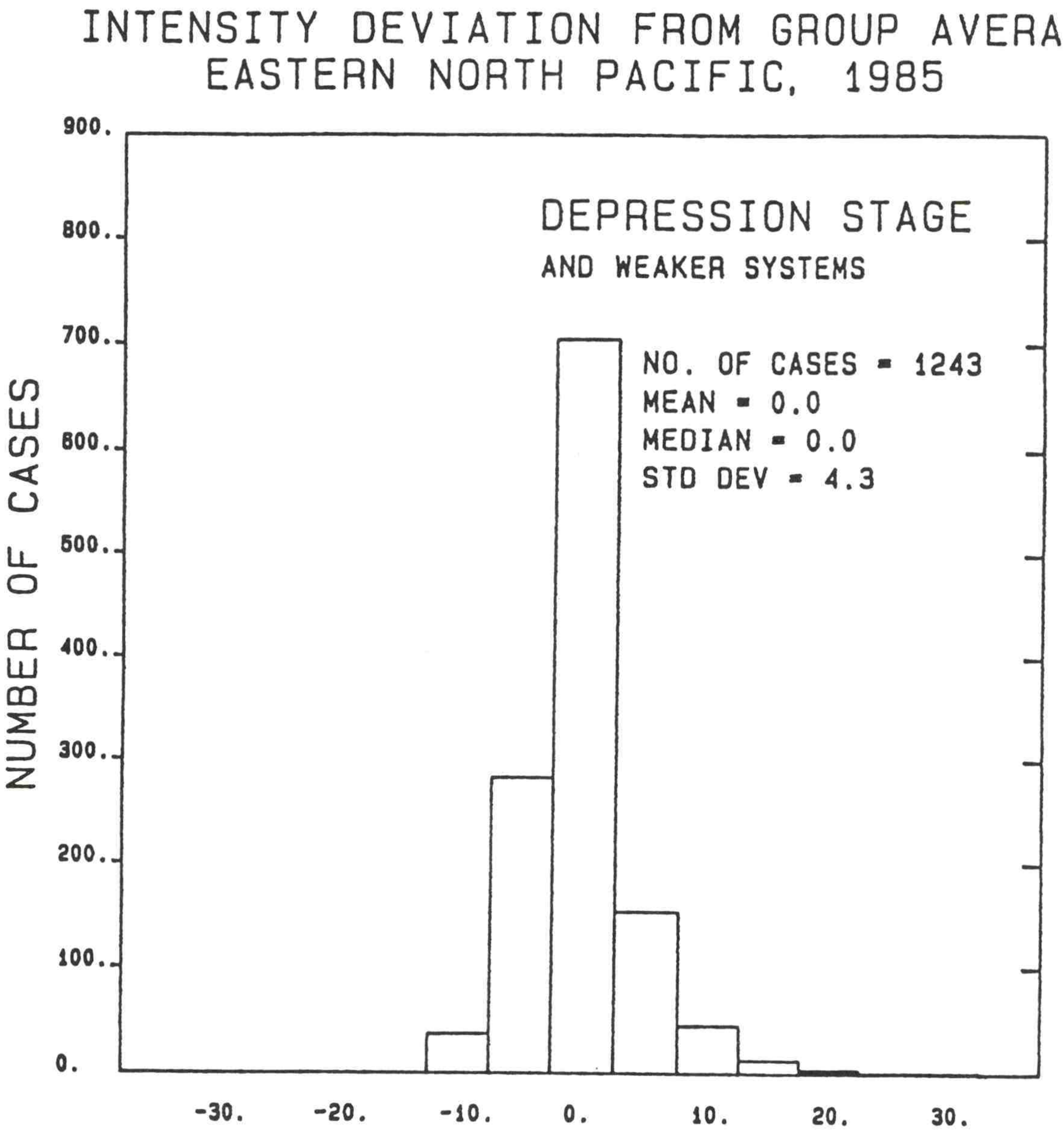


Figure 2-6. Deviations (knots) of individual satellite-determined intensity estimates from the group average for the tropical depression stage and weaker systems.

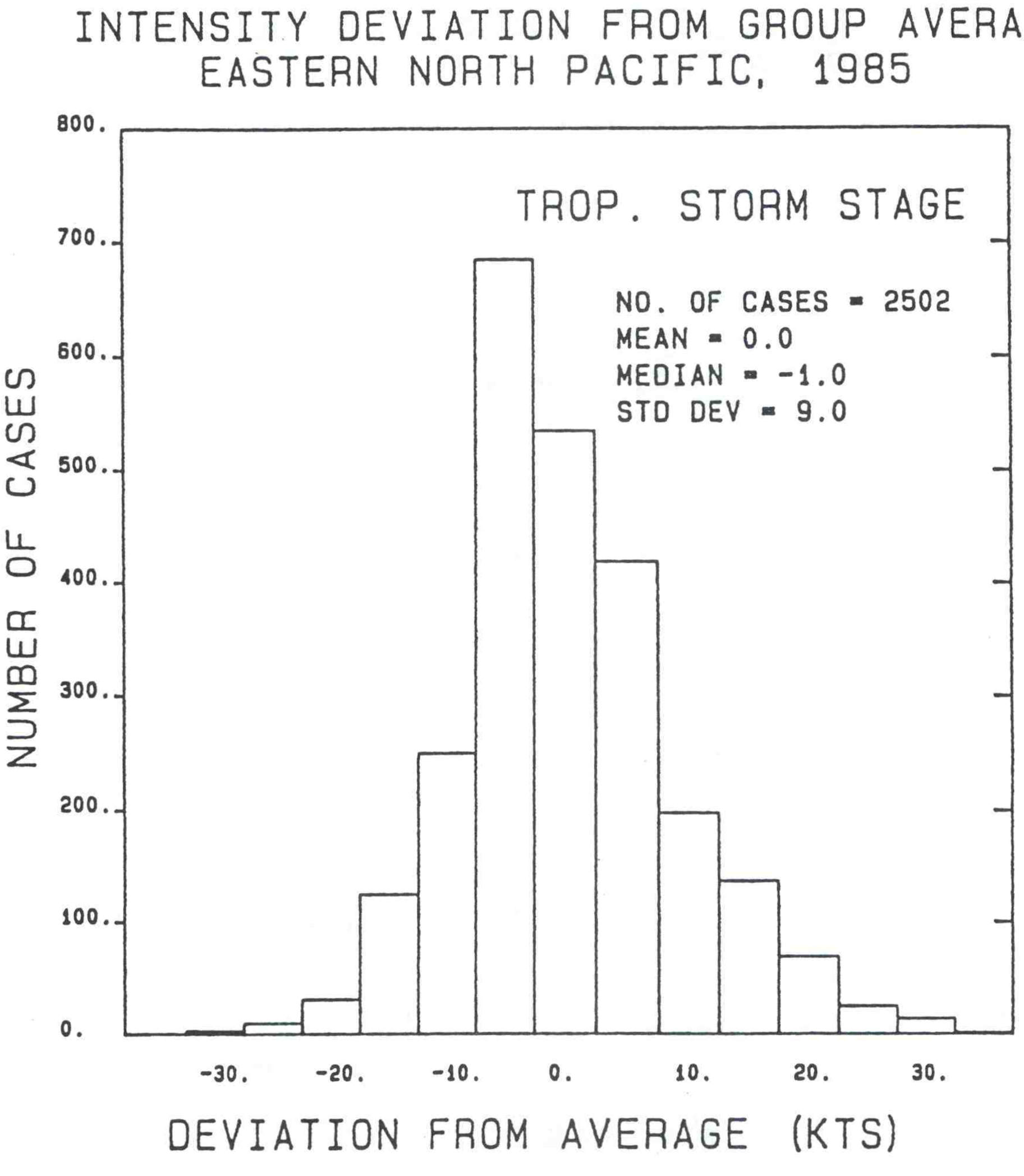


Figure 2-7. Deviations (knots) of individual satellite-determined intensity estimates from the group average for the tropical depression stage and weaker systems.

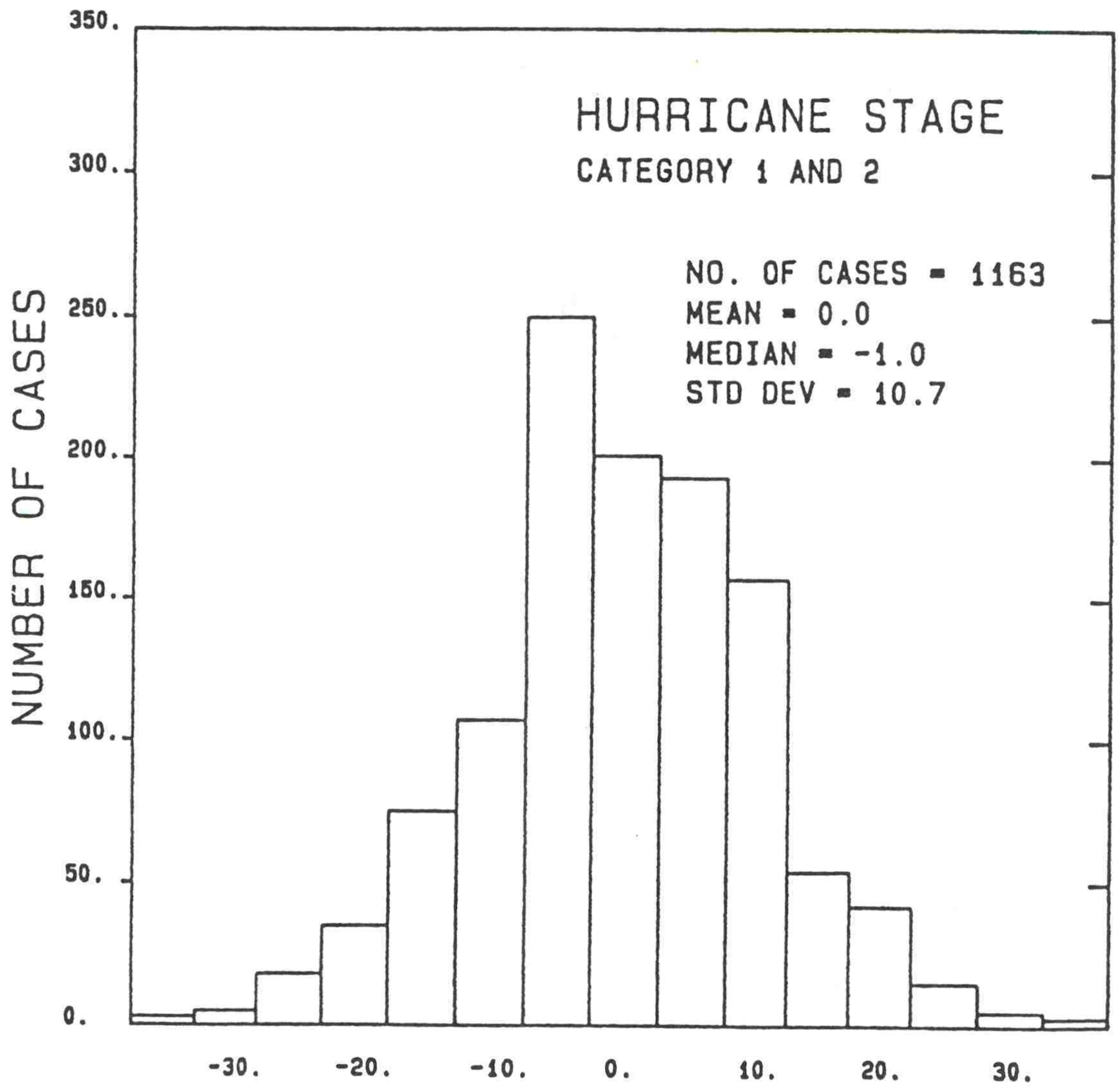


Figure 2-8. Deviations (knots) of individual satellite-determined intensity estimates from the group average for the category 1 and 2 hurricane stage.

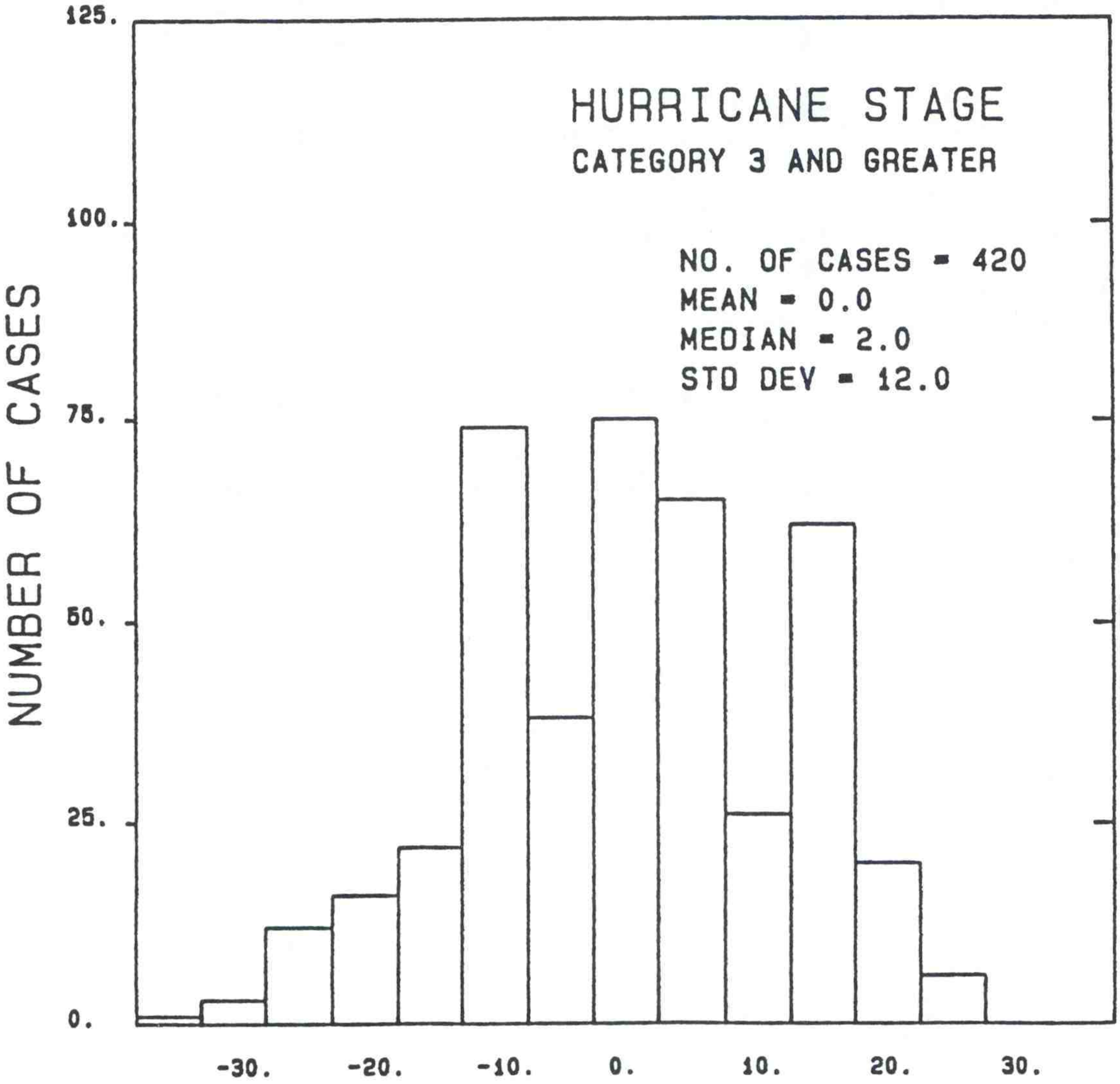


Figure 2-9. Deviations (knots) of individual satellite-determined intensity estimates from the group average for the category 3 and greater hurricane stage.

2.6.3. In an operational environment some decrease in the dispersion of position estimates for the weaker cyclone stages may be expected with the use of animation of satellite imagery, particularly of high resolution visible imagery. The operational and more objective use of digital infrared satellite data, described in the Dvorak technique, will also result in a definite decrease in the dispersion of intensity estimates in the cyclone stages in which an eye is present. However, the subjectivity involved in estimating the position and intensity of many cyclones without well-defined eyes will continue to result in differences, even from this single data source. The occasional large satellite position or intensity misinterpretation could result in inaccurate warnings, with a corresponding increase in the loss of lives and property.

Acknowledgment. The authors wish to gratefully acknowledge the help of the fourteen analysts from the NHC and the SAB in making the numerous satellite classifications. This study would not have been possible without their time and effort.

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PART 3

RESULTS OF A TROPICAL CYCLONE ACCURACY STUDY USING POLAR ORBITING SATELLITE DATA

by

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3.1. Introduction

3.1.1. During the 41st Interdepartmental Hurricane Conference at Homestead Air Force Base, Florida, two conference action items stimulated the Office of the Federal Coordinator for Meteorological Services and Supporting Research (OFCM) to convene an Ad Hoc Group for Tropical Cyclone Studies under the Committee for Basic Services. The tasks for the groups were to determine the state-of-the-art of satellite tropical cyclone interpretation accuracies and to assess the effect of not having dedicated aerial reconnaissance on 24-, 48-, and 72-hour forecast accuracy. The OFCM requested that the Air Force, Navy, the National Environmental Satellite, Data, and Information Service (NESDIS), the National Hurricane Center (NHC), and Eastern Pacific Hurricane Center (EPHC) participate.

3.1.2. The OFCM task entailed four major phases:

- To conduct studies to assess the accuracy of satellite derived tropical cyclone positions and intensities.

- To use the results of the studies to update a similar study by Sheets and Grieman (1975).

- To apply the results to computer models and attempt to calculate the effects on forecast output, i.e., sensitivity analyses.

- To perform an economic analysis based partially on the results of the computer sensitivity analyses. (The economic analysis would not be conducted by the Ad Hoc Group, but probably by some outside agency or contractor.)

3.1.3. On April 15, 1987, OFCM conducted a meeting of the Ad Hoc Group for Tropical Cyclone Studies at Rockville, Maryland where the specific tasks, strategies, and milestones for the study were established to accomplish Phases 1, 2, and 3. Air Weather Service (AWS) agreed to conduct a study at the Air Force Global Weather Central (AFGWC), Offutt Air Force Base, Nebraska, evaluating tropical cyclone locations and intensities using Defense Meterological Satellite Program (DMSP) and National Oceanic and Atmospheric Administration (NOAA) polar orbiting satellite data. The NHC, EPHC, and NESDIS agreed to determine positioning and intensity accuracies using geostationary satellite data from GOES EAST and GOES WEST. The Navy and the National Weather Service agreed to perform the sensitivity analyses. The

data acquisition and analysis phases of the studies required more time than anticipated and only preliminary results were presented at the 42nd Interdepartmental Hurricane Conference at Homestead Air Force Base, Florida, held in January 1988.

3.2. Methodology

3.2.1. The Air Weather Service (AWS) requested that forecasters at the Joint Typhoon Warning Center (JTWC), Guam, provide polar orbiting and geostationary satellite data of ten 1984, 1985, and/or 1986 tropical cyclones. The JTWC forecasters selected six of their most difficult, erratically moving tropical cyclones from 1986. Tropical cyclone in this study ranged in intensity from 30 to 110 kt. The tracks of these storms are illustrated in Figure 3-1. Due to time and manpower constraints, only the polar orbiter data of six tropical cyclones were analyzed. Personnel at Headquarters Air Weather Service Directorate of Aerospace Services geographically gridded each of the pieces of imagery--over 300 in all--and determined correction factors for each.

3.2.2. Next, the images were catalogued by individual tropical cyclone and put into chronological order for four time periods per day at approximately 6-hr intervals near 00, 06, 12, and 18 UTC. Some interim data between the standard 6-hourly synoptic times were also included when available. The individual storms were given a code number, denying analysts knowledge of the tropical cyclone name and the year in which it occurred.

3.2.3. In September 1987, the images were delivered to AFGWC and discussions were held with the experiment manager at AFGWC to familiarize him with the procedures and ground rules decided upon at the April 15, 1988 OFCM meeting. The ground rules and procedures were based on those used during the 1975 study by Sheets and Grieman to allow comparisons between data sets. These rules did impose several limitations that are discussed in Section 3.3. A major strength of the study methodology was that it disallowed analysts the use of aircraft reconnaissance data in making their satellite position and intensity estimates. Sheets and McAdie (1988) and Martin (1988) have discussed the historical influence of aircraft data on satellite estimates and have attempted to quantify the effects of the aircraft contamination.

3.2.4. AFGWC selected four satellite analysts with tropical cyclone fix experience ranging from 5 months to 2 years. Other operational commitments precluded using the most experienced analysts at AFGWC. Each analyst determined 6-hourly tropical cyclone center locations and 12-hourly intensity estimates using the Dvorak technique. Occasionally, an analyst also provided fix information on interim imagery as well. Where an analyst occasionally skipped an image, no attempt was made to determine the reason or to obtain the missed analysis.

3.2.5. Participants received imagery for each 6-hr period, beginning with the first available imagery set for the disturbance. After the position analysis and Dvorak intensity classification were made, the analyst was given the next 6-hourly imagery set. The analysts were allowed to keep the earlier imagery sets, but could not go back and alter their earlier analyses and classifications based on the later data. During the experiment, analysts

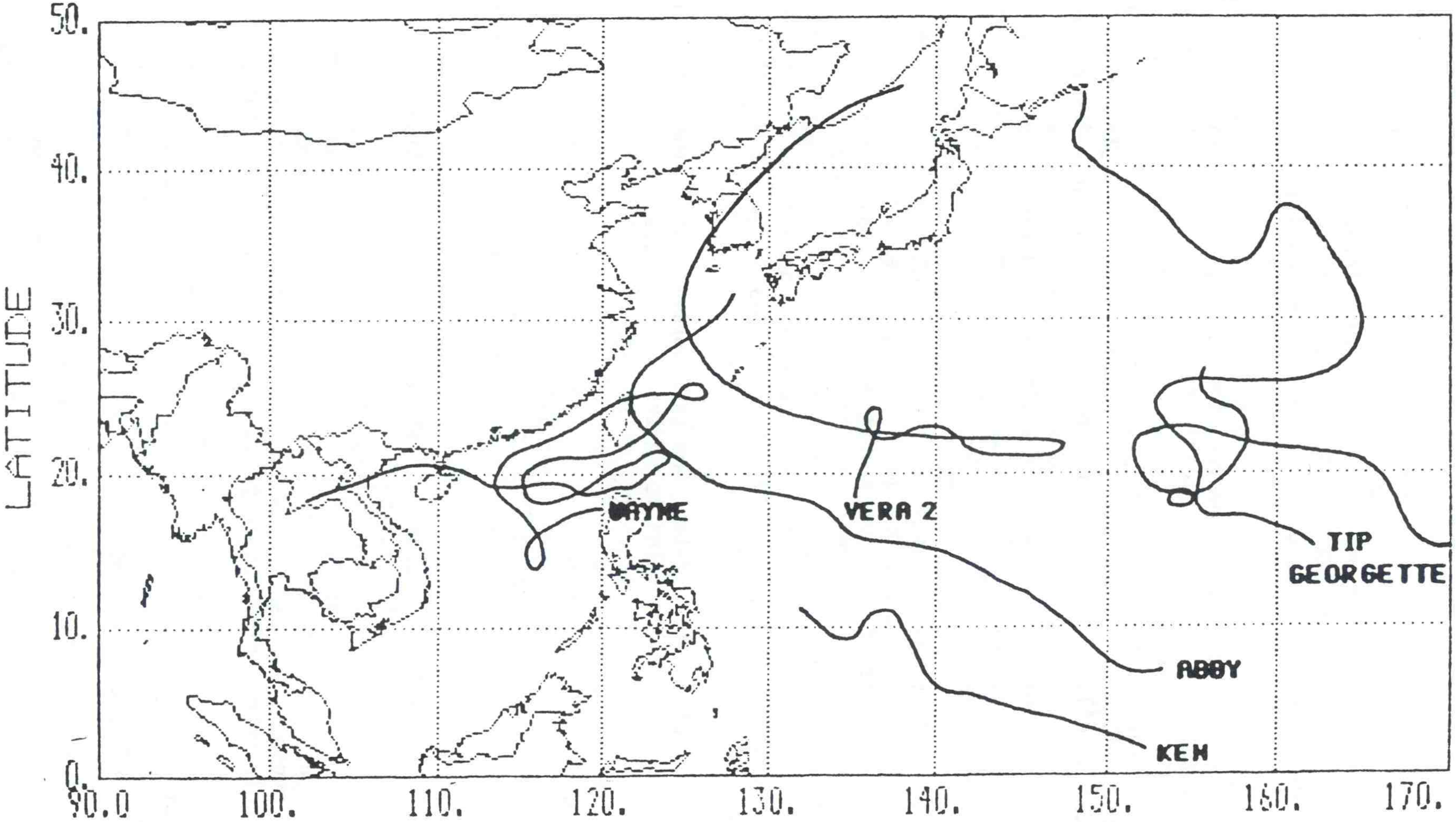


Figure 3-1. Tracks of the 1986 tropical cyclones used in this study.

worked alone and did not discuss the project with other participants. Nor was any other information, aside from the imagery, made available to the analysts. After all analyses were completed, the calculations of each analyst were returned to Headquarters Air Weather Service Directorate of Aerospace Sciences where the results were processed and interpreted.

3.3. Limitations The ground rules and procedures of the experiment imposed several limitations that excluded many of the benefits of existing technology and of operational procedures specifically designed to enhance the use of meteorological satellite data. The limitations included poor continuity, lack of synoptic data, no analyst-analyst or analyst-forecaster interaction, no quality control, no real-time geographical gridding, incomplete meteorological satellite data sets, and no geostationary satellite animation. Thus, the results presented in this study probably underestimate current operational polar orbiting satellite capabilities; however, many of the limitations were necessary to filter out any influence from aerial weather reconnaissance. Limitations are discussed below.

3.3.1. Poor continuity. Analysts normally maintain continuity charts of their fix positions, but did not do so during the experiment. They also normally have knowledge of the operational best track positions from the warnings. These pieces of information generally help preclude very large errors and reduce inconsistencies in sequential satellite analyses. In addition, very little interim satellite data were available in the imagery sets--data that are routinely available to the analyst and are valuable for improving continuity.

3.3.2. Lack of synoptic data. Analysts normally have synoptic data available. Ship reports are valuable in the early stages of tropical cyclone development where multiple centers may exist, and may help the analyst isolate a particular cloud mass or portion of a cloud system. Reports from aircraft of opportunity, upper-air data from rawinsondes, and numerical analysis and forecast products--data not available to the analyst--are important for estimating steering flow and vertical shear. Low level winds and vorticity centers from geostationary satellites can also help isolate circulation centers.

3.3.3. No analyst-analyst or analyst-forecaster interaction. The adage, "two heads are better than one," has a great deal of validity in the satellite analysis business. One analyst may see something another analyst misses or interprets differently. Forecasters have the most up-to-date knowledge of synoptic data, including radar reports, and of computer forecast and analysis products and can discuss such information with the satellite analysts to help them refine future positions and intensity estimates.

3.3.4. No quality control. The AWS normally uses on-the-spot and after-the-fact quality control to eliminate most geographical gridding errors and large positioning errors and to assure that Dvorak classification rules and continuity rules are adhered to.

3.3.5. No real time geographical gridding. For this experiment, geographical gridding of the imagery was accomplished at Headquarters, Air Weather Service. Gridders were well-trained but had no prior gridding experience. Latitude corrections were made by moving the imagery up or down

on the grid to place geography at the correct latitude as determined from General Navigation Charts (accurate to within 3 nmi). Longitude corrections were then made using a precision sliding scale to measure the differences between the "correct" longitude of a geographical feature and its location on the imagery. A resulting error value was then recorded so that it could later be appropriately added to or subtracted from the storm fix longitudes determined by analysts at AFGWC in order to obtain the corrected storm fix longitudes. Errors can occur when analysts erroneously add instead of subtract the corrections or vice versa. Analysts frequently grid off of two geographical points on different sides of the imagery to correct for satellite yaw. For the experiment, only one geographical point was used and yaw corrections were not made. In addition, some data could not be gridded with the available imagery enhancements.

3.3.6. Incomplete satellite data sets. Under normal operational conditions, analysts obtain several different imagery products from a single satellite pass in order to derive the most accurate center fix and Dvorak intensity classification. For example, when analyzing a nighttime DMSP pass, the analyst would routinely obtain 0.3 nmi infrared data, 1.5 nmi nighttime visual (visible spectra) data (if illumination were sufficient), and an enhanced infrared (EIR) photograph using the Dvorak enhancement scale (Dvorak, 1984). The working data sets used in this study included very little nighttime visual data and were frequently missing the Dvorak enhancement image. The NOAA satellite 3.7 micrometer channel is frequently used for nighttime gridding and for isolating exposed low level circulation centers and low cloud orientation. These data were frequently not available in the data sets as well. Daytime imagery sets generally included a visual image (0.3 nmi for DMSP and 0.55 nmi for NOAA) and a 1.5 nmi infrared image. Enhanced infrared Dvorak images were available for about 60 percent of the cases. When the EIR images were missing, analysts had to revert back to the older, less reliable Dvorak technique that uses visual imagery.

3.3.7. No geostationary satellite animation. Animation techniques using hourly or half-hourly geostationary satellite imagery have greatly improved positioning from geostationary satellites. The geostationary data provide valuable continuity for polar orbiting satellite analysis. Animation is especially valuable for daytime positioning of poorly organized storms since it allows the analyst to track vorticity centers and low level cloud movement. Sheets, et al. (1988) indicate that tropical cyclone positions from half-hourly animated geosynchronous data are generally more accurate than those from polar orbiting satellites, especially for storms of less than hurricane intensity.

3.4. Storm Positioning--Discussion and Results. Sheets and Grieman (1975) identified three primary sources of error when a tropical cyclone is positioned using satellite data. First, there are variations in gridding. Proper geographical gridding of the imagery and accurate ephemeris data which predicts future satellite locations can generally alleviate most of these variations. Second, different analysts may pick different center locations for the same storm from the same picture. The deviations associated with this aspect of positioning error refer to internal consistency. Third, the analyzed position deviates from the actual storm position. The deviations associated with this error refer to absolute accuracy. As Sheets and Grieman (1975) point out, the absolute accuracy is the most difficult source

of error to determine because of the lack of knowledge of ground truth. Since aerial reconnaissance was available in the western North Pacific during 1986 and was flown in each storm in the data set, we can be somewhat confident that the final JTWC best track compiled from all data after the fact is a reasonably good measure of the actual storm location. Another source of error is due to limitations in the accuracy of the plotting charts on which the satellite imagery geographical gridding is based and on which the best track is plotted. The charts used by the JTWC and AFGWC are accurate to within 3 nmi.

3.4.1. Variations in gridding. Polar orbiting satellite data generally contain errors from several sources: attitude (i.e., pitch, role, and yaw) of the spacecraft; timing errors caused by a higher or lower altitude than expected; timing errors due to the spacecraft moving faster or slower than expected; timing errors due to non-precise spacecraft and ground processing; system clock settings; software truncation of computational data; and mechanical stretching of the imagery medium, whether film or paper. Spacecraft attitude and timing variations, which lead to inaccurate ephemeris, generally cause the largest errors and lead to the desirability to geographically grid the data. The errors in the ephemeris can be overcome by having precision clocks at ground processing sites and by updating the ephemeris daily (Dr. Otis Brown, personal communication).

3.4.1.1. The DMSP's 0.3 nmi resolution visual data allow geographical gridding using very small Pacific atolls. The nighttime visible DMSP mode (1.5 nmi resolution) also allows gridding from city lights. Gridding is most accurate for a storm fix if the analyst has identifiable geography near the same latitude as the storm or along a line passing through the storm and parallel to the satellite subtrack. If a spacecraft has a history of yaw, the analyst will make grid corrections from two geographical points, if available, on opposite sides of the data (e.g., upper left and lower right) so that the imagery can be properly rotated. If geographical gridding is not possible, the analyst must rely on the ephemeris that is based on the projected location of the spacecraft as determined from knowledge of the satellite's past location and attitude. The DMSP has two positioning modes on the spacecraft. The primary mode uses a precision pointing platform to provide a pointing accuracy of 0.6 nmi. The secondary (backup) mode provides an accuracy of 6 nmi. Correctly gridded DMSP data are usually accurate within 3 to 4 nmi. The DMSP ephemeris is normally accurate within 2 to 4 nmi, but errors can be as large as 15 nmi if the ephemeris is not updated frequently enough. For this reason, data are geographically gridded.

3.4.1.2. The NOAA satellite's 0.55 nmi visual resolution data allow gridding from small atolls near the satellite subtrack, but near the edge of scan the resolution deteriorates to about 9 nmi, and less precise geographical features can be used. The 3.7 micrometer channel of the NOAA satellites enables analysts to accurately locate geography where land-ocean temperatures show good thermal contrast. As with the NOAA visual data, the NOAA infrared resolution deteriorates near the edge of scan. The accuracy of geographically gridded NOAA data will generally vary from about 3 nmi near satellite subtrack to about 10 nmi near the edge of scan. NOAA ephemeris is usually accurate within 4 nmi, but errors as large as 25 nmi have been observed whenever the ephemeris is not updated at least on a weekly basis.

3.4.1.3. Sheets and Grieman (1975) indicated gridding accuracies of 15 nmi, 30 nmi, and 10 nmi for ATS, ESSA, and DMSP satellites, respectively. Table 3-1 summarizes the estimated mean gridding accuracy for current DMSP and NOAA satellites based on five years of tracking satellite location errors at JTWC, AFGWC, and Clark Air Base, Philippines. The slightly poorer NOAA geographical gridding accuracy primarily results from poorer resolution away from satellite subtrack, while the poorer NOAA ephemeris accuracies are more a reflection of the frequency of updating the ephemeris than the actual satellite accuracy. Satellite pointing accuracy, stability, and altitude consistency have greatly improved since 1975, and have contributed to more accurate gridding, based on both geography and the ephemeris. The values in Table 3-1 for both DMSP and NOAA are estimates, and probably underestimate the actual accuracies somewhat. The geographical gridding accuracies could be improved by automating the gridding process using the highly accurate World Data Base II geography data base. This process has recently been implemented at AFGWC and should result in improved position accuracy.

Table 3-1. Estimated gridding accuracies of DMSP and NOAA satellites based on geography and ephemeris.

	Cumulative percent	Estimated Accuracy (Geographical Gridding)	Estimated Accuracy (Ephemeris Gridding)
DMSP	90	< 3 nmi	< 2 nmi
	95	< 4 nmi	< 4 nmi
	99	< 5 nmi	< 6 nmi
	100	< 6 nmi	< 15 nmi
NOAA	90	< 3 nmi	< 4 nmi
	95	< 4 nmi	< 6 nmi
	99	< 6 nmi	< 10 nmi
	100	< 10 nmi	< 25 nmi

3.4.2. Variation of Tropical Cyclone Center Locations Determined by Different Analysts--Internal Consistency. The second source of positioning error is that caused by separate analysts picking a different storm center location from the same picture. This results from different subjective interpretations of the same cloud features by different analysts. It also results from different interpretations in employing positioning and intensity techniques which are not totally objective. As Sheets and Grieman (1975) point out, internal consistency is relatively easy to determine. Table 2 shows the variation between tropical cyclone center locations which were determined from the same imagery by different analysts. To determine this variation, the position determined by the "most experienced analyst" was chosen as the reference position. The positions determined by the remaining three analysts were then compared to the reference position to arrive at the variations. This methodology differs from that of Sheets and Grieman (1975)

who used points along a derived best satellite track as their reference positions. It also differs from that of Mayfield, et al. (1988) who used the centroid of positions. These previous types of techniques, by estimating the "mean" of the majority of positions, should be expected to produce smaller average variations (less scatter) than the technique used in this study since there is no guarantee that the most experienced analyst will have the smallest error. While this technique provides a more accurate measurement of actual internal consistency, the studies of Sheets and Grieman (1975) and Mayfield, et al. (1988) probably provide a better assessment of internal consistency from an operational perspective. Time and manpower limitations prevented using the "centroid" technique in this study.

Table 3-2. Variations of tropical cyclone center locations derived by different analysts as determined from the distance deviation between the positions derived by the "most experienced analyst" (D) and those derived by the other analysts (A, B, and C). Deviations are in nautical miles (nmi).

Analyst	Mean Deviation	Standard Deviation	% < 20 nmi	% < 40 nmi	% < 60 nmi
A (D-A)	17.9	18.8	68	88	95
B (D-B)	13.8	16.8	79	92	97
C (D-C)	17.2	20.5	68	86	95
All	16.3	18.6	71	80	96

Table 3-2 shows a relatively small mean deviation of 16.3 nmi between the position of the most experienced analyst and those of the other analysts. On average, 71 percent of the deviations were less than 20 nmi, 89 percent were less than 40 nmi, and 96 percent were less than 60 nmi. Analyst B, who had comparable experience to the most experienced analyst, had smaller deviations than the less experienced analysts, as expected.

3.4.3. Figures 3-2 through 3-5 illustrate the distribution of the deviations of position from the positions of the most experienced analyst, for various intensity ranges. Some of the deviations were large (4 percent exceeded 60 nmi), but as expected, the deviations became smaller with increasing storm intensity. Figure 3-2 illustrates the deviations of the positions of analysts A, B, and C from the positions of the most experienced analyst for all cyclones of tropical storm intensity. The columns represent 5-nmi increments, where the first column contains values from 0 to 4 nmi, the second 5 to 9 nmi, and so on. The distribution shows that 50 percent of the deviations are greater than 20 nmi with 10 percent being greater than 50 nmi. Figure 3-3 depicts the deviations for typhoons with intensities less than 85 kt. The mean deviation is 15.8 nmi, with 50 percent being greater than 10 nmi and 10 percent being greater than 50 nmi. The same depiction for

TROPICAL STORMS

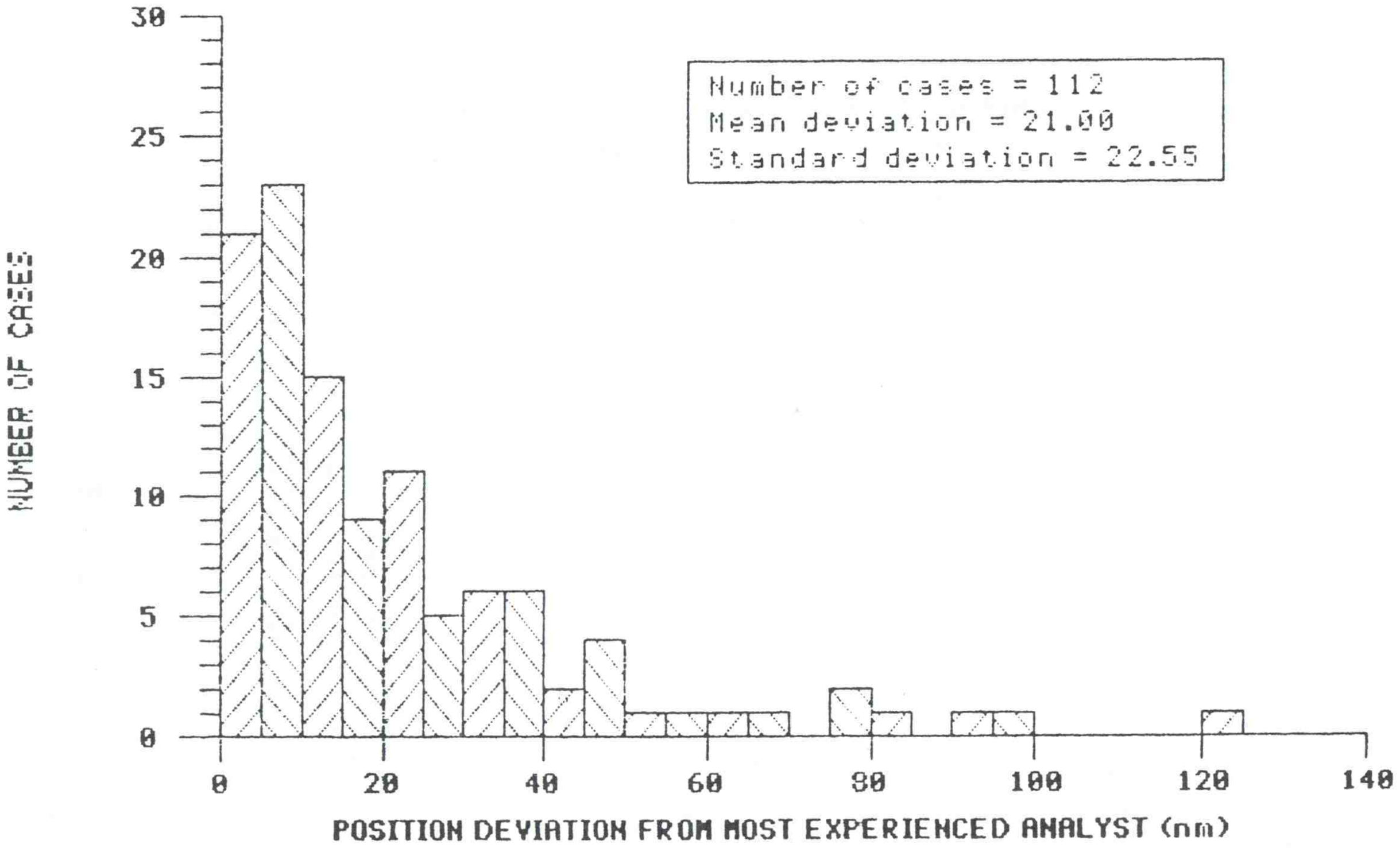


Figure 3-2. Deviations (nmi) of positions determined by three analysts from the positions determined by the most experienced analyst for tropical storms.

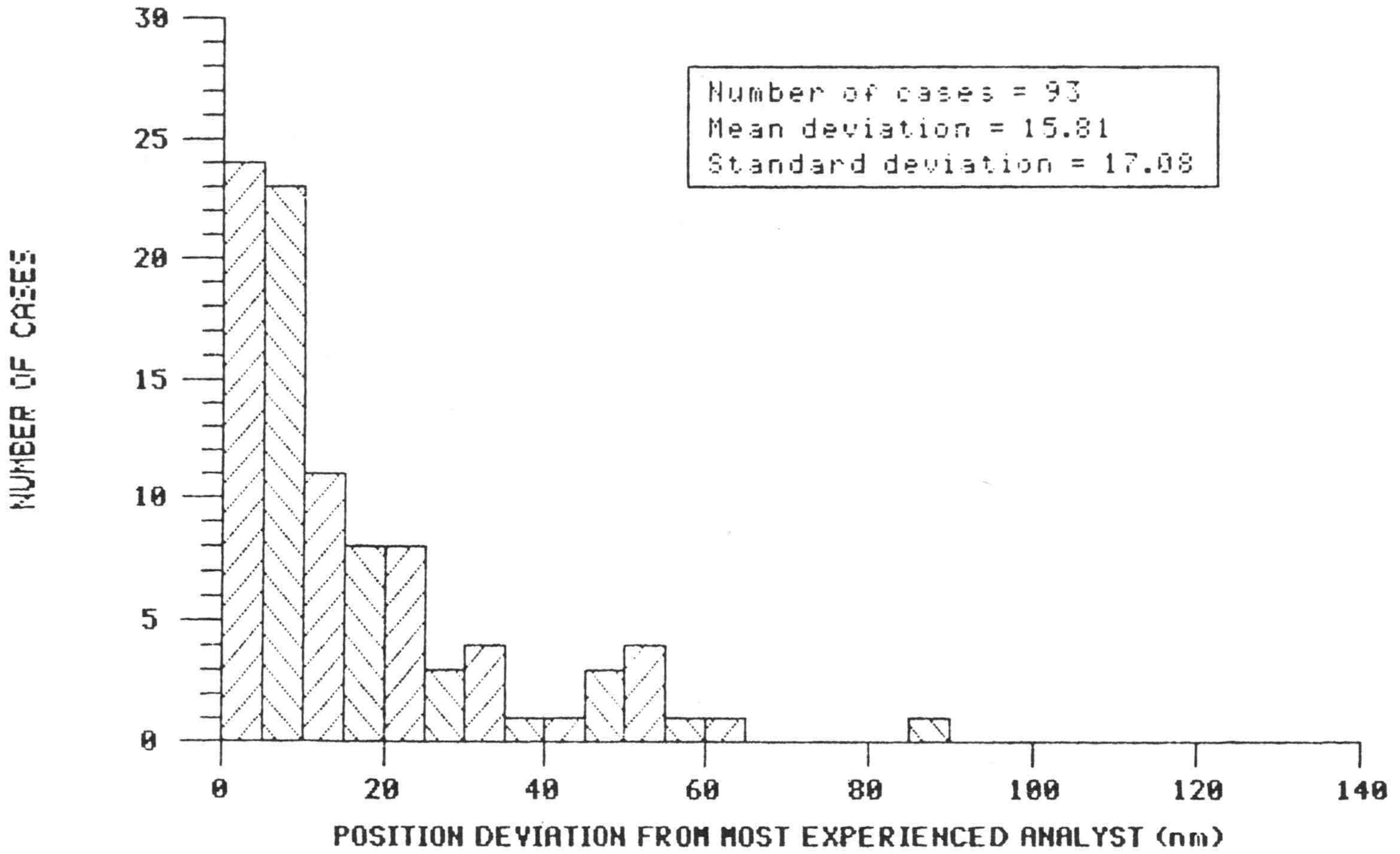


Figure 3-3. Deviations (nmi) of positions determined by three analysts from the positions determined by the most experienced analyst for typhoons with intensities less than 85 kt.

TYPHOONS ≥85 KT

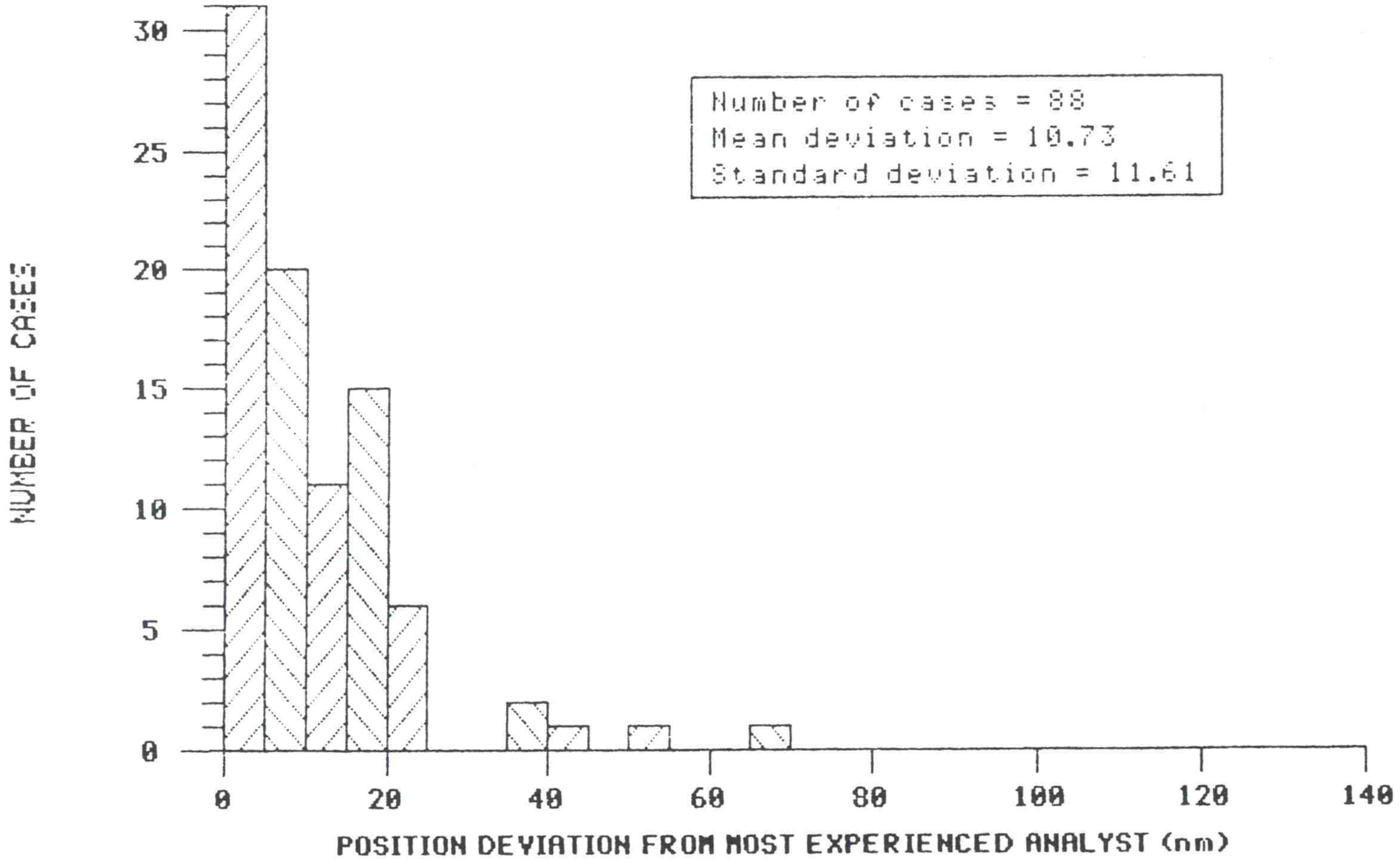


Figure 3-4. Deviations (nmi) of positions determined by three analysts from the positions determined by the most experienced analyst for typhoons with intensities of 85 kt or greater.

ALL STORMS

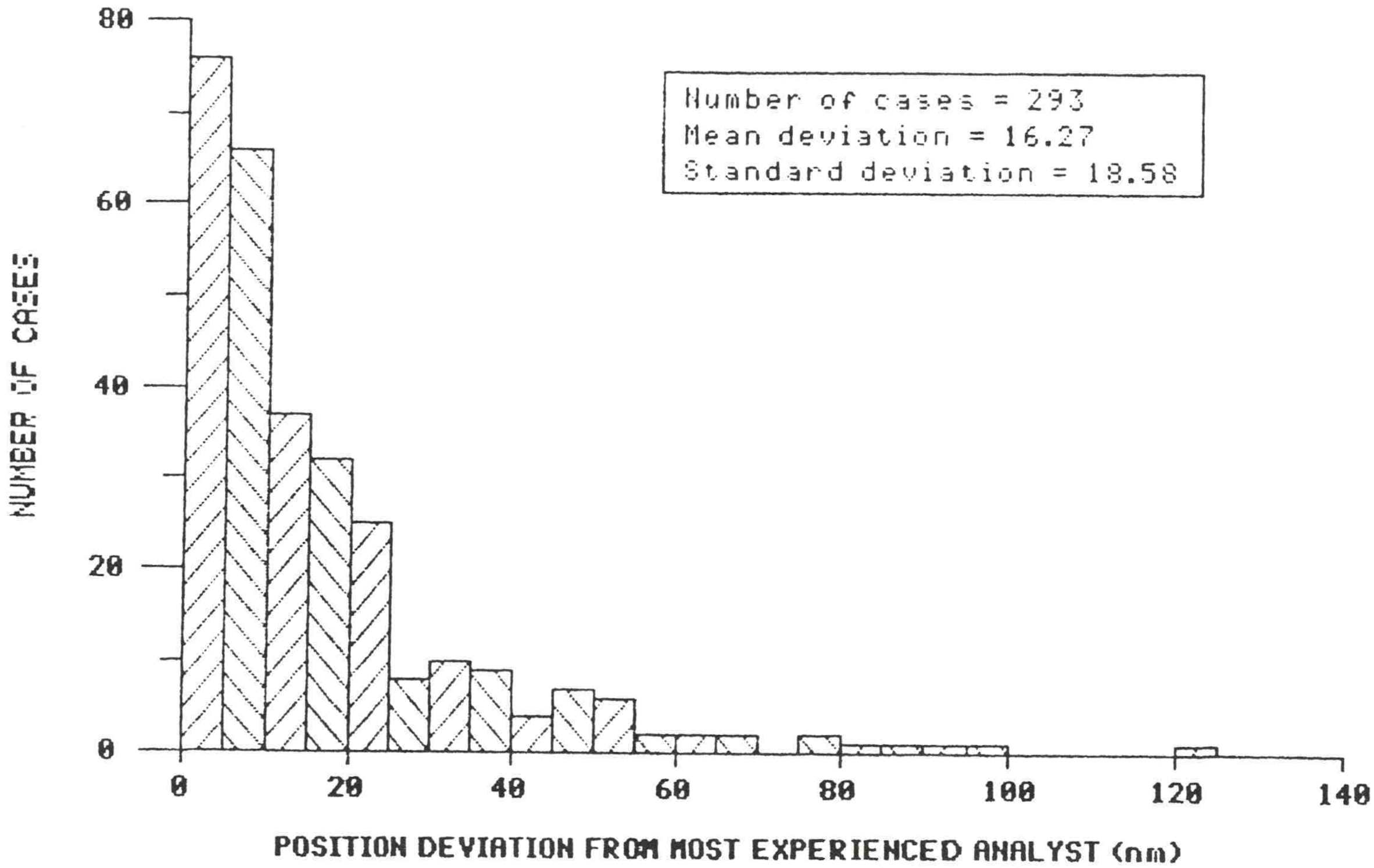


Figure 3-5. Deviations (nmi) of positions determined by three analysts from the positions determined by the most experienced analyst for all tropical cyclones in this study.

typhoons of intensities between 85 and 110 kt is represented in Figure 3-4 where 50 percent of the deviations were greater than 8 nmi and 10 percent were greater than 20 nmi. Figure 3-5 depicts the deviation for all storm intensities. Here, 50 percent of the deviations were greater than 11 nmi while 10 percent exceeded 45 nmi.

3.4.4. Deviation of Tropical Cyclone Center Locations from the Official Best Track Locations--Absolute Accuracy. The third source of positioning error is the deviation of the satellite-derived position from the actual storm center position. Even if different analysts derive identical center locations, that location may deviate from the actual surface location as shown by ground truth data. As Sheets and Grieman (1975) point out, exact ground truth is nearly impossible to obtain. The "official best track," compiled after-the-fact from all available data, is probably the best estimate of ground truth, but it appears to be biased toward aircraft data (Sheets and Grieman, 1975). The commonly used Dvorak positioning technique uses visual or infrared satellite data to describe rainband and central cloud features that are then applied to a set of rules to determine the most likely storm center location. The greatest difficulty arises when the center is obscured by cirrus, and the upper and lower circulation centers are not vertically aligned. Such misalignment is usually the result of vertical wind shears, which may not be easily determined. Even if determined their effects may not be correctly interpreted.

3.4.5. Table 3-3 shows the deviation between tropical cyclone center locations derived by the four analysts and the actual positions as determined from the official best track. As with the internal consistency study, the methodology in this study differs from that of Sheets and Grieman (1975) who derived positions from a best satellite track which they then compared with the respective best track positions to arrive at the absolute accuracies. Again, values arrived at from the methodology used in this study should be expected to be larger.

3.4.6. Table 3-3 illustrates the importance of experience in determining tropical cyclone positions. The most experienced analyst, D, had a smaller error and a smaller standard deviation than the least experienced analyst, C. More than 90 percent of analyst D's positions were within 60 nmi of the respective best track positions, while 75 percent of analyst C's positions were within 60 nmi. Stratification of the errors according to tropical cyclone intensity showed, as expected, that the errors got smaller as the tropical cyclones got stronger. Cyclones of tropical storm intensity averaged errors around 40 nmi, while typhoons of 85 kt and greater had mean errors less than 20 nmi. Furthermore, 98 percent of the stronger typhoons had errors less than 60 nmi. In contrast, only 76 percent of the tropical storms had errors less than 60 nmi.

3.4.7. Figures 3-6 through 3-9 show the distribution of the errors in 5 nmi increments (0-4 nmi, 5-9 nmi, etc.). Figure 3-6 illustrates the large range of errors for the tropical storms, where 50 percent of the errors were greater than 33 nmi and 10 percent were greater than 85 nmi. Figure 3-7 shows the smaller range of errors for the typhoons with intensities less than 85 kt. Here, 50 percent of the errors were greater than 24 nmi, while 10 percent were greater than 60 nmi. With typhoons equalling or exceeding 85 kt (Figure 3-8), the 50 percent and 90 percent cummulative values were 16 nmi

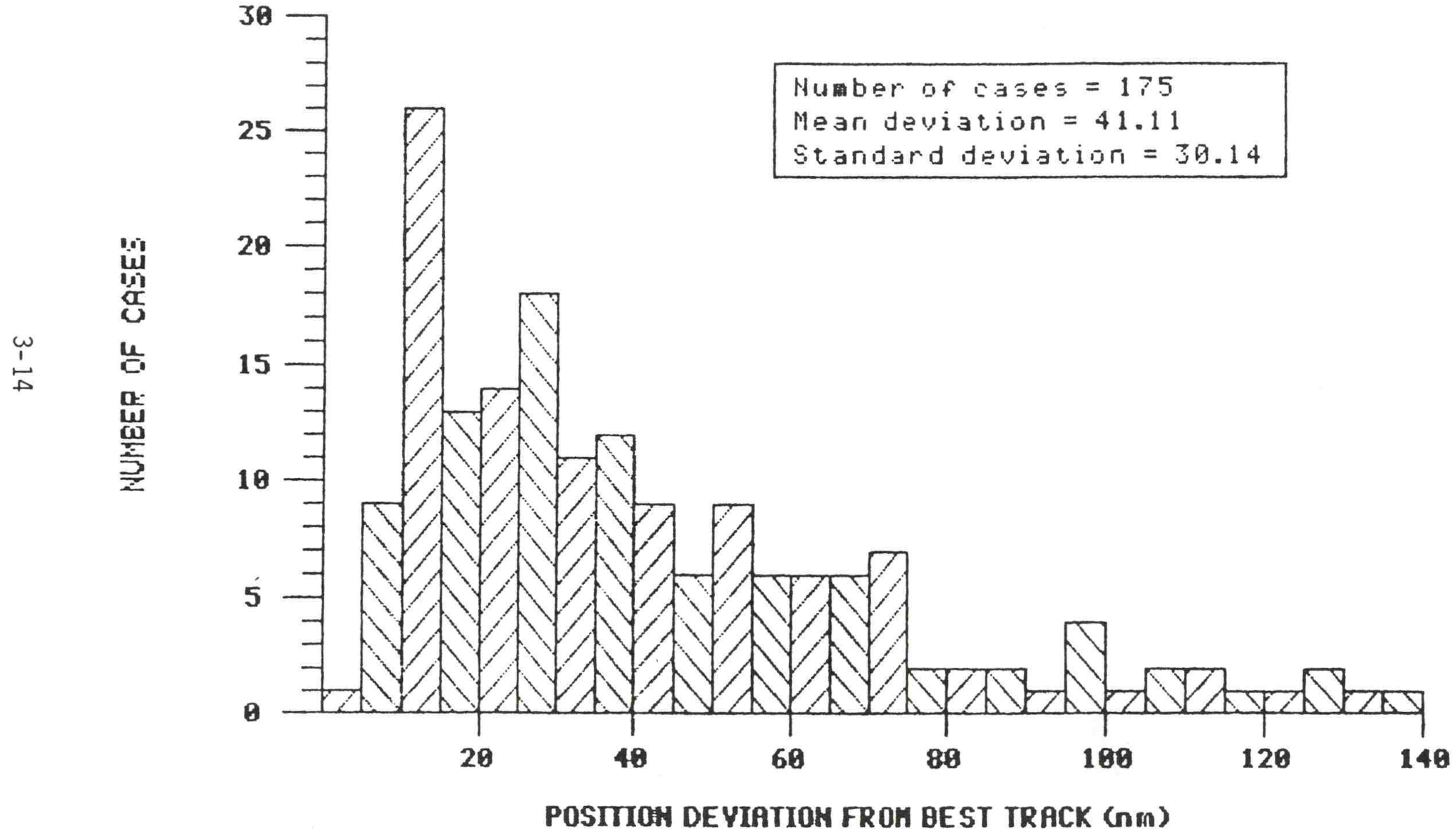


Figure 3-6. Deviations (nmi) of positions determined by all four analysts from the best track positions for tropical storms.

TYPHOONS <85 KT

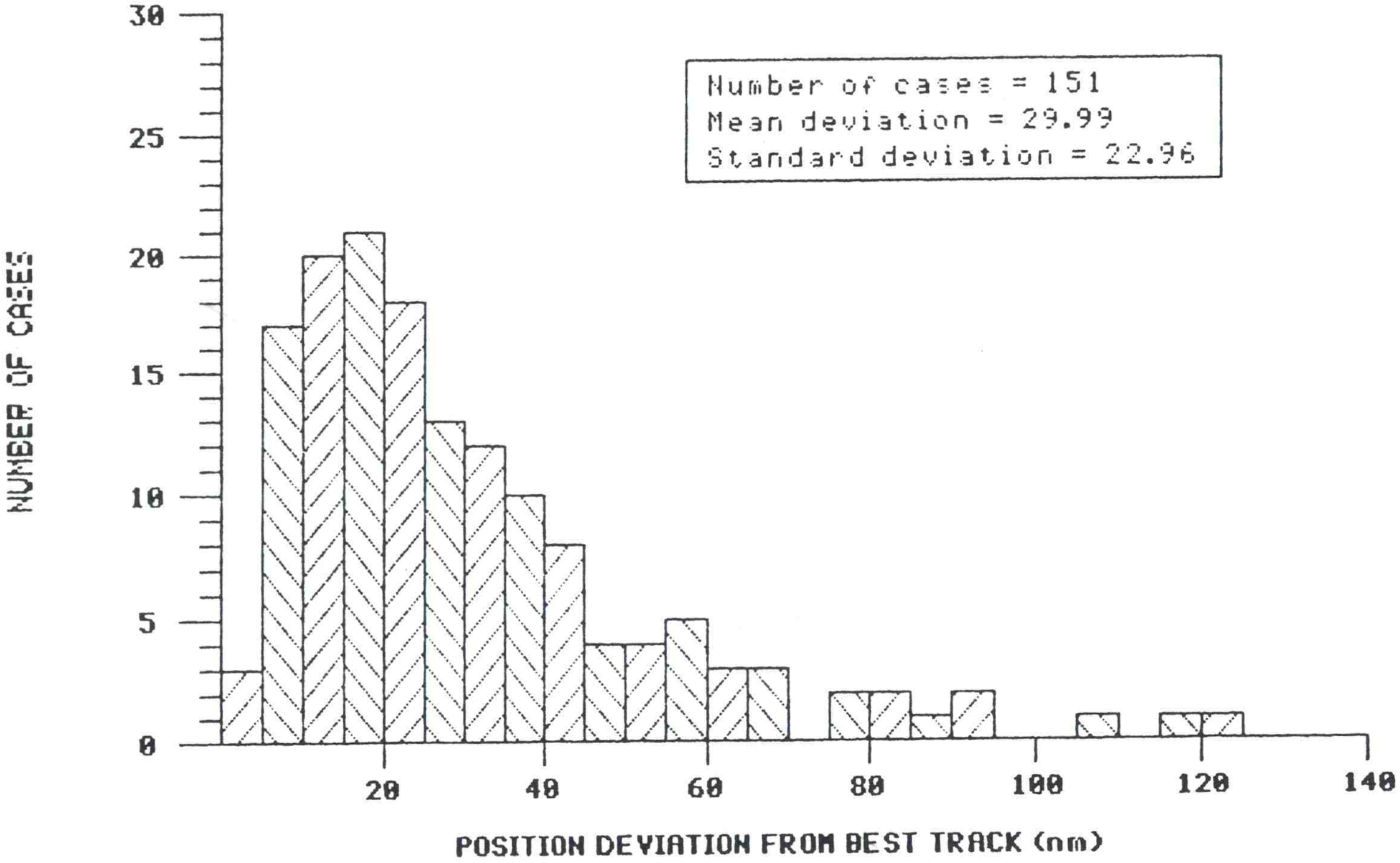


Figure 3-7. Deviations (nmi) of positions determined by all four analysts from the best track positions for typhoons with intensities less than 85 kt.

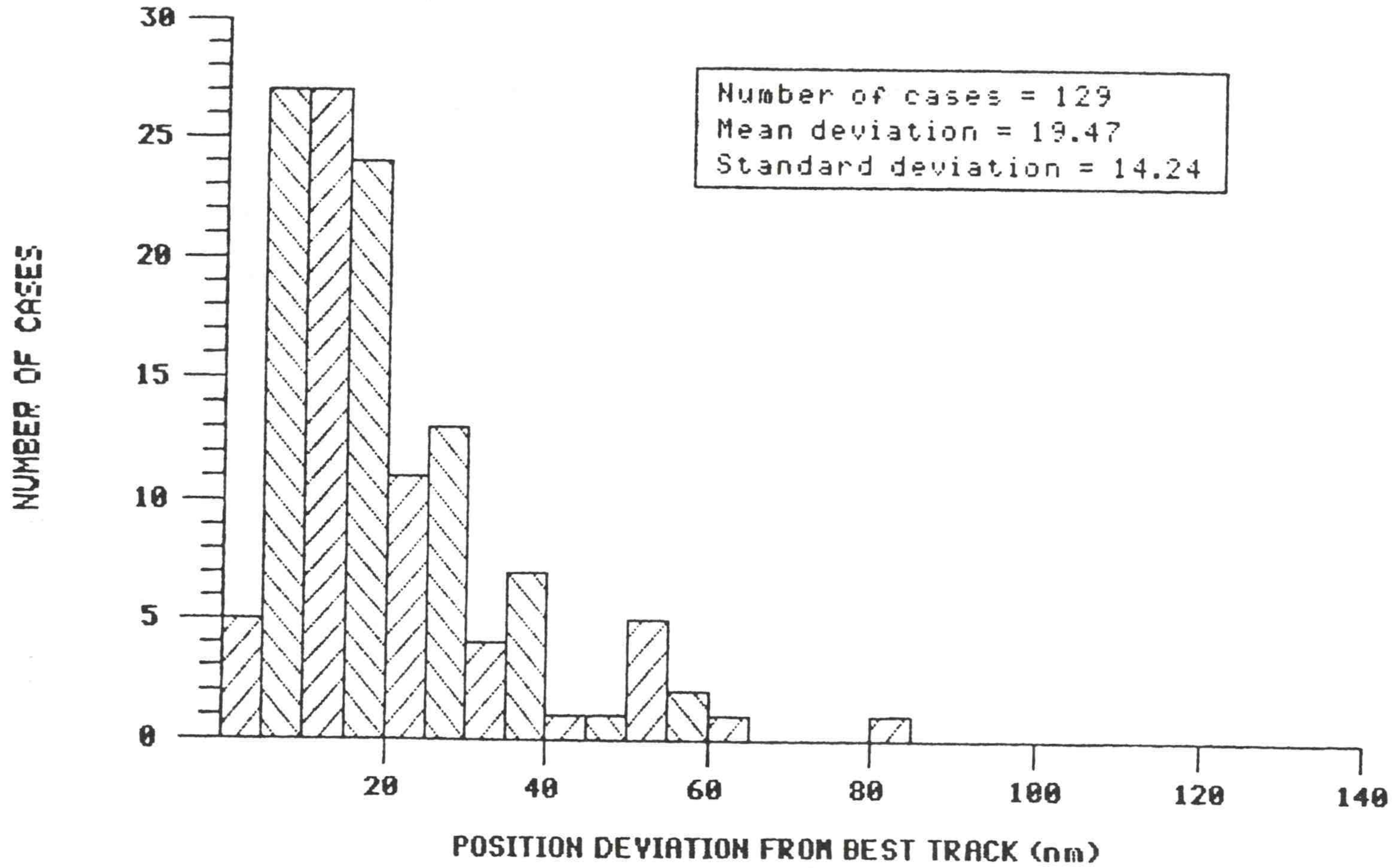


Figure 3-8. Deviations (nmi) of positions determined by all four analysts from the best track positions for typhoons with intensities equal to or greater than 85 kt.

ALL STORMS

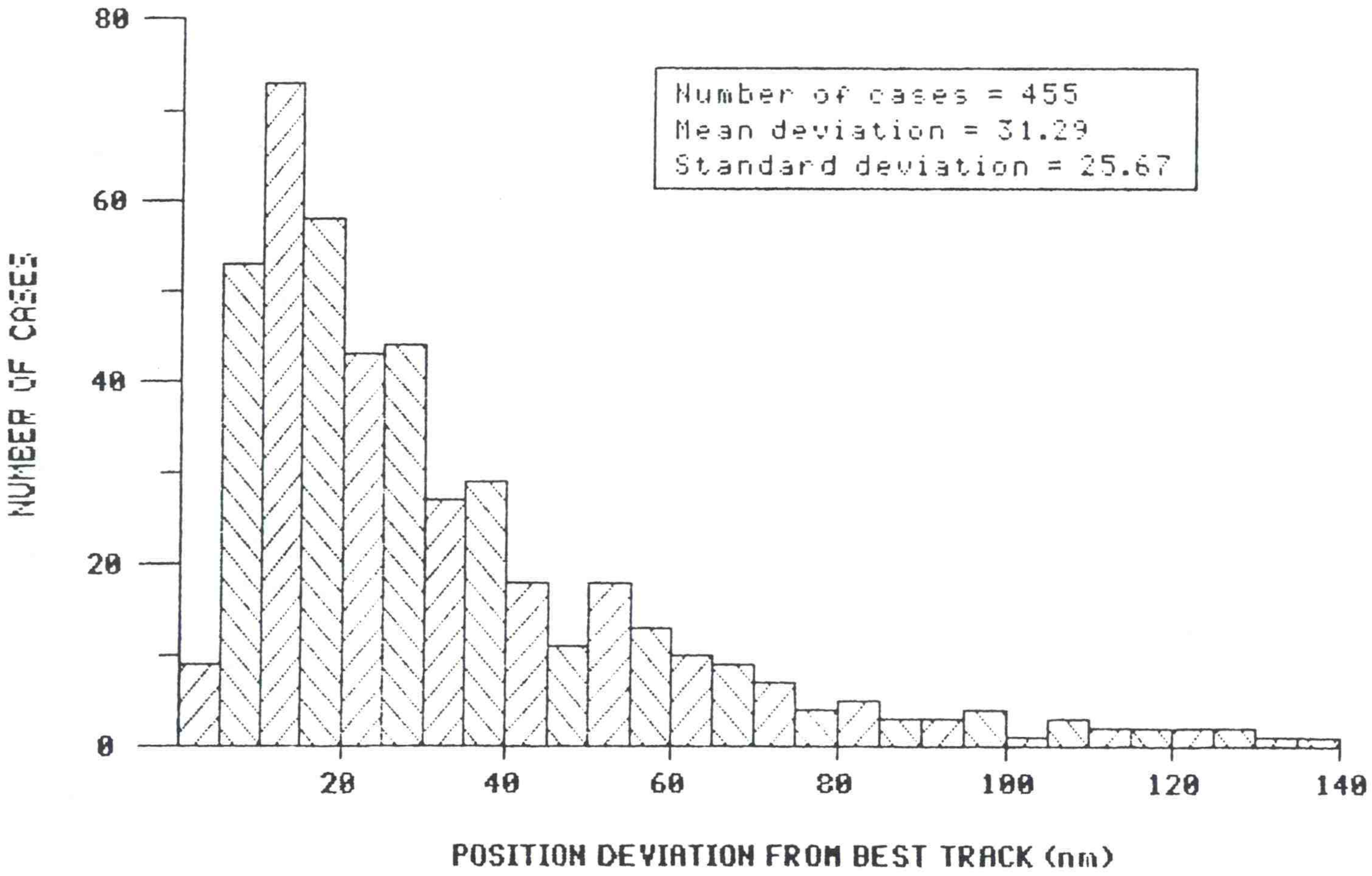


Figure 3-9. Deviations (nmi) of positions determined by all four analysts from the best track positions for all tropical cyclones in the study.

and 36 nmi, respectively. Figure 3-9 depicts the distribution of errors for all storm intensities. The mean deviation was about 31 nmi, while the 50 and 90 percent cumulative values were 23 nmi and 65 nmi, respectively.

Table 3-3. Deviation between tropical cyclone locations derived by analysts and those derived from the official best track with respect to individual analyst and storm intensity.

All storms

Analyst	Mean Deviation	Standard Deviation	% < 20 nmi	% < 40 nmi	% < 60 nmi
A	31.2	24.5	45	71	86
B	30.5	25.9	42	69	89
C	34.6	29.0	39	70	75
D	28.8	21.7	43	75	91
All analysts	31.3	25.7	42	71	85
Intensity Range					
<65 kt	41.1	27.4	30	60	76
≥65 kt <85 kt	30.0	23.0	40	77	89
≥85 kt	19.5	14.2	64	91	98

3.4.8. Table 3-4 shows that positions derived from DMSP satellite imagery were slightly greater than 1 nmi more accurate than those derived from NOAA satellite imagery. This small difference is surprising since DMSP has slightly better subtrack resolution, a constant cross-scan resolution, better position pointing accuracy, and a more frequently updated ephemeris. Positions derived from DMSP data were more accurate for tropical storms and strong typhoons, but unexpectedly, the positions derived from the NOAA satellites were more accurate for the weaker typhoons. A comparison of position accuracy based on a combination of visual spectra imagery and infrared spectra imagery (daytime) versus those based primarily on infrared imagery only (nighttime) from both the DMSP and NOAA satellites shows that positions using visual data averaged about 4.5 nmi better accuracy. This is expected since the visual imagery has better resolution and better identifies both low and high level cumulus elements. Positions derived using visual data averaged more than 8 nmi better accuracy for tropical storms and a little more than 3 nmi better accuracy for stronger typhoons. However, the differences between positions derived from visual and infrared data for weaker typhoons were less than 1 nmi.

Table 3-4. Comparison of tropical cyclone center position accuracies as a function of polar orbiting satellite platform and imagery type for different tropical cyclone intensities. All values are in nautical miles (nmi).

	DMSP		NOAA		Visual		Infrared	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
< 65 kt	40.0	26.0	44.1	38.7	37.2	29.5	45.5	30.3
≥ 65 kt < 85 kt	30.8	24.7	28.9	20.6	29.7	20.0	30.3	25.1
≥ 85 kt	16.9	12.8	23.8	15.4	17.9	14.3	21.3	14.0
All	30.9	24.6	32.0	27.5	29.2	24.4	33.7	26.8

3.5. Tropical Cyclone Intensity

3.5.1. Satellite techniques used to derive tropical cyclone intensities have two primary sources of error (Sheets and Grieman, 1975): variations between analysts and calibration of the technique.

3.5.1.1. The variation between analysts can be determined by having several trained analysts apply the same satellite intensity technique to the same imagery data sets, then comparing the resulting intensity estimates. To determine the variation between analysts, this study compares the intensity estimates independently derived by three analysts applying the Dvorak intensity technique to the intensity estimates of a fourth analyst designated as the most experienced analyst.

3.5.1.2. The calibration of the technique is a more difficult process. The technique must be correlated with maximum sustained wind speed near the surface. For several reasons that are well-discussed in Sheets and Grieman (1975) and Black and Adams (1983), minimum surface pressure is a better measure of maximum intensity than is maximum observed wind speed. However, Atkinson and Holliday (1977) and Lubeck and Shewchuk (1980) indicate that mean deviations between maximum surface wind speed and minimum sea level pressure are 8 and 20 kt, respectively. Individual deviations can be much larger, especially during the development stage of a tropical cyclone and when a tropical cyclone moves into higher latitudes (poleward of 30 degrees latitude). So while the smoothed aircraft tropical cyclone positions are probably a good estimate of the actual tropical cyclone positions, the aircraft derived intensities are not as good an indicator of the actual maximum intensities. Thus, the more conservative satellite signature is likely a better determinant of maximum intensity than is the minimual sea level pressure under certain conditions. While the official best track is highly biased toward aircraft-derived intensity data, it is probably the best available indicator of actual storm intensity. The relationship between Dvorak current intensity (C.I.) number, maximum mean sustained wind speed, and minimum sea level pressure is shown in Table 3-5.

3.5.1.3. To determine the absolute accuracy of intensity estimates in this study, the Dvorak C.I. numbers (Dvorak 1984) derived by the four analysts for a specific image were compared with a derived C.I. number based on the official best track intensity for the time of the image.

Table 3-5. The empirical relationship between the current intensity (C.I.) number, the maximum mean wind speed (MWS), and the minimum sea level pressure (MSLP) in tropical cyclones. The MSLP values for the NW Pacific were recommended in Shewchuk and Weir (1980). (Dvorak, 1984).

C.I. Number	MWS (kt)	MSLP (kPa) (Atlantic)	MSLP (kPa) (NW Pacific)
1	25		
1.5	25		
2	30	100.9	100.0
2.5	35	100.5	99.7
3	45	100.0	99.1
3.5	55	99.4	98.4
4	65	98.7	97.6
4.5	77	97.9	96.6
5	90	97.0	95.4
5.5	102	96.0	94.1
6	115	94.8	92.7
6.5	127	93.5	91.4
7	140	92.1	89.8
7.5	155	90.6	87.9
8	170	89.0	85.8

3.5.2. Variations of Storm Intensity as Determined by Different Analysts--Internal Consistency. As with determination of the position variations, the intensity variations were derived by using the "most experienced analyst" as the reference analyst. Intensity estimates of the remaining three analysts were compared with those of the reference analyst to determine the intensity variations. Table 3-6 illustrates the internal consistency between intensity estimates, stratified according to tropical cyclone intensity.

3.5.2.1. For tropical storms, 25 percent of the intensity analyses were in the same C.I. category as the C.I. analysis of the most experienced analyst, while 100 percent were within 1.5 C.I. numbers. From Table 3-5, we can see that the 1.5 C.I. number deviation amounts to about 25 kt. The cummulative distributions are similar for weaker typhoons. Deviations are higher for stronger typhoons with 91 percent of the analysis deviations being within 1.5 C.I. numbers.

3.5.2.2. Figures 3-10 through 3-13 depict the C.I. number deviations of intensity derived by the three less experienced analysts from the C.I. number derived by the most experienced analyst for tropical cyclones

TROPICAL STORMS

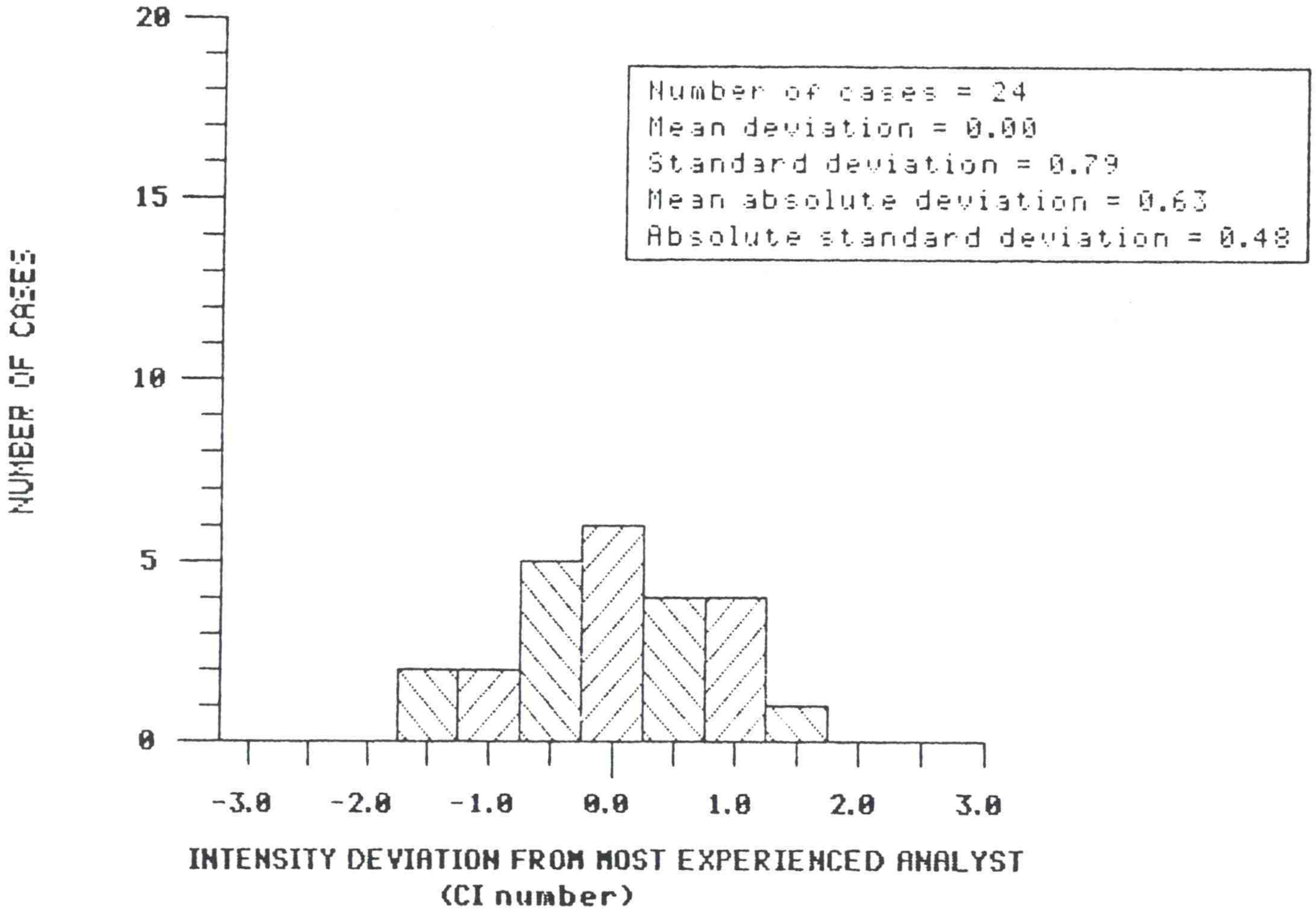


Figure 3-10. Deviations in C.I. numbers of intensities determined by three analysts from the intensities determined by the most experienced analyst for tropical storms.

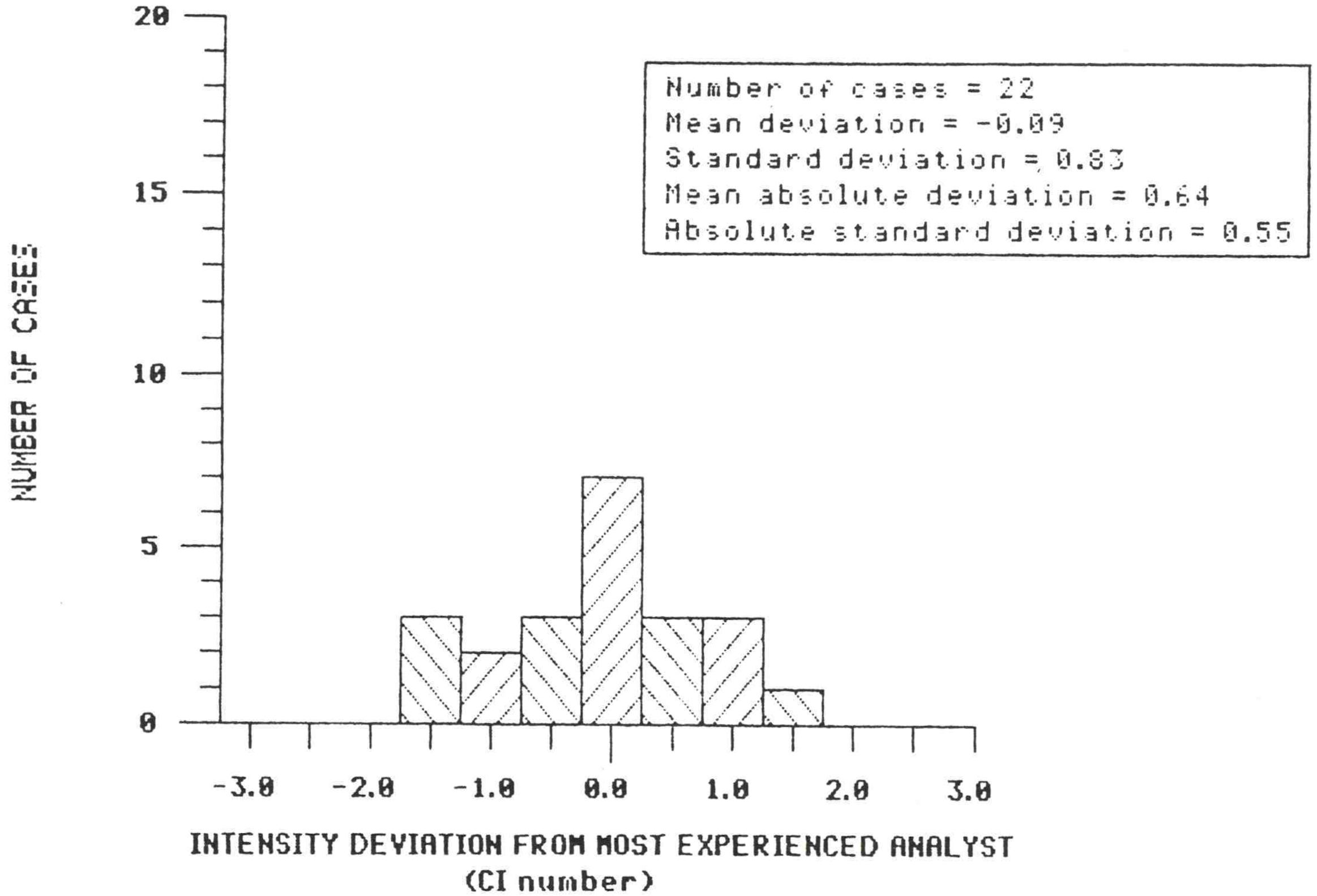


Figure 3-11. Deviations in C.I. numbers of intensities determined by three analysts from the intensities determined by the most experienced analyst for typhoons with intensities less than 85 kt.

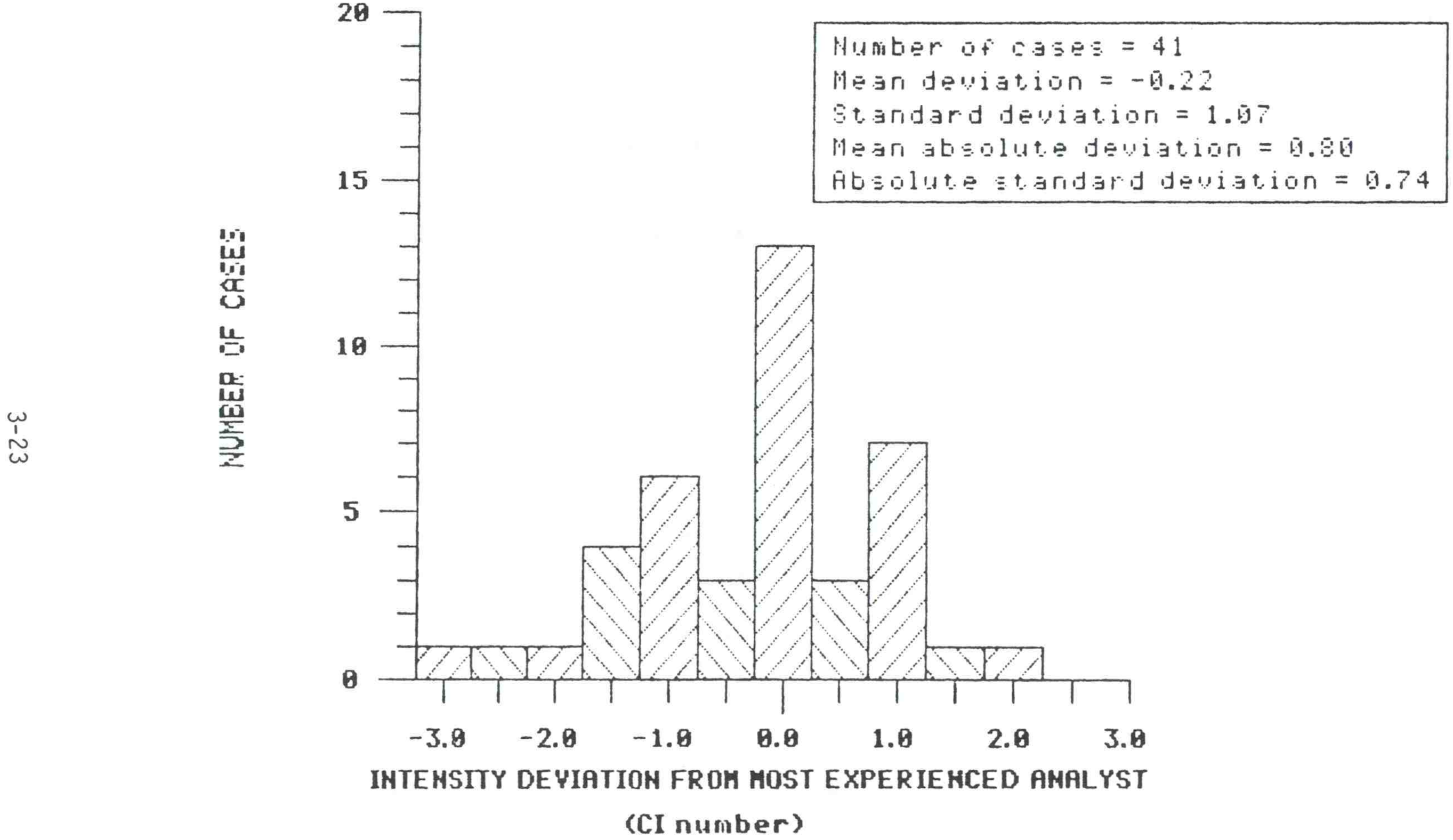


Figure 3-12. Deviations in C.I. numbers of intensities determined by three analysts from the intensities determined by the most experienced analyst for typhoons with intensities greater than or equal to 85 kt.

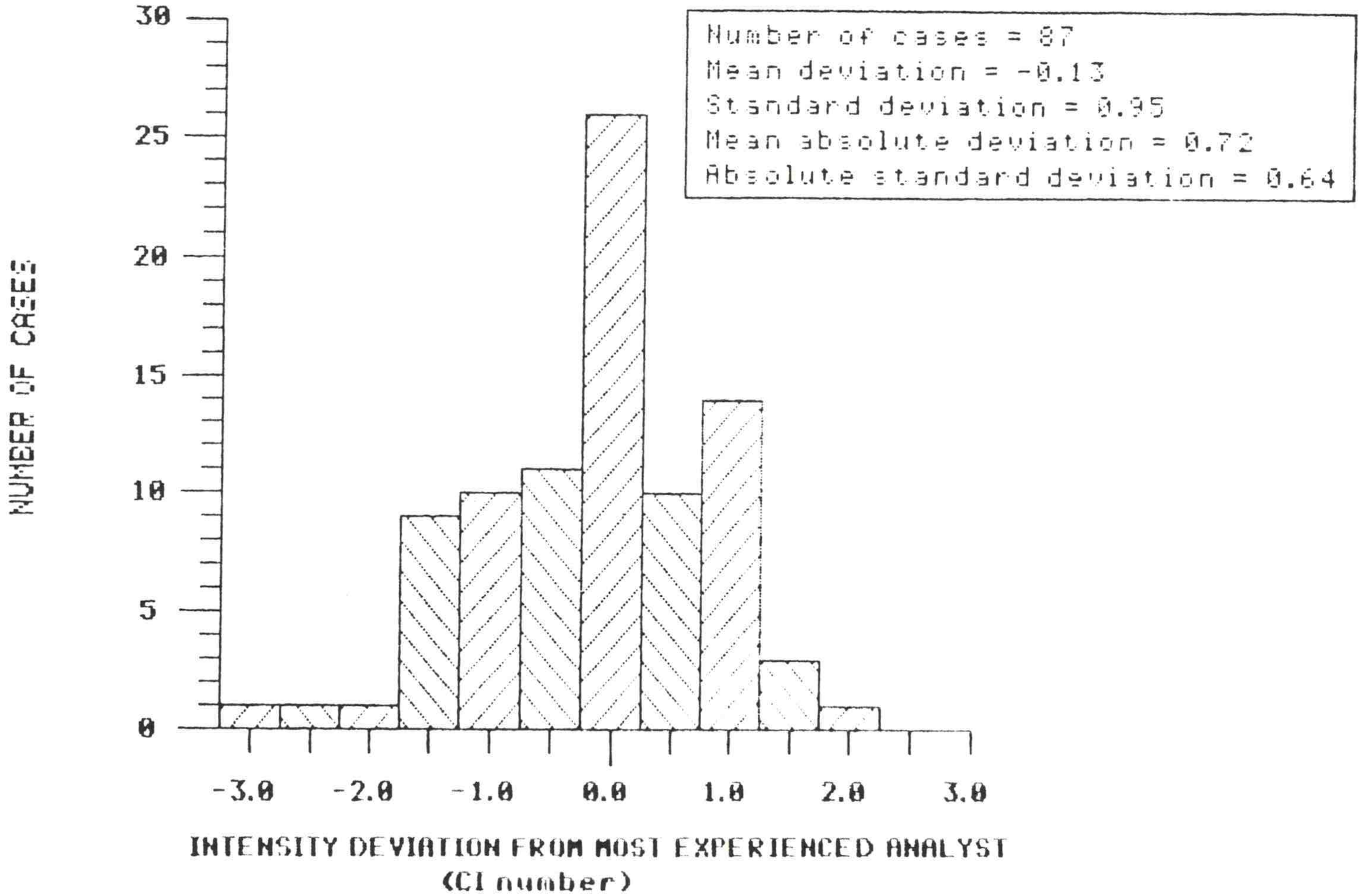


Figure 3-13. Deviations in C.I. numbers of intensities determined by three analysts from the intensities determined by the most experienced analyst for tropical cyclones of all intensities.

Table 3-6. Mean deviations of the derived current intensity (C.I.) numbers of three analysts from the C.I. number of the most experienced analyst.

Intensity	No. of Cases	Deviations 0		± 0.5		± 1.0		± 1.5	
		% in Cat	% in Cat	Cum %	% in Cat	Cum %	% in Cat	Cum %
< 65 kt	24	25	38	63	25	88	12	100
≥ 65 kt < 85 kt	22	32	27	59	23	82	18	100
≥ 85 kt	41	32	15	47	32	79	12	91
All	87	30	24	54	28	82	15	97

of various intensities. Although the sample size is small, some general observations can be made from the data. As discussed above, deviations for tropical storms and weaker typhoons, were within 1.5 C.I. numbers. Figure 3-12 shows that the deviations become larger with more intense typhoons. While there was no noticeable bias in deviations associated with tropical storms, there was a tendency for the less experienced analysts to derive weaker intensities than the most experienced analyst for typhoons. This negative bias increased with increasing typhoon intensity.

3.5.3. Deviation of Analyzed Current Intensity (C.I.) Number From Official Best Track Intensity--Absolute Accuracy.

3.5.3.1. As discussed in the previous section, the official best track intensity is probably the best available measure of actual intensity. To determine absolute accuracy, the intensity estimates made by each analyst were compared with those of the official best track for the same time period. The resulting deviation was taken as a measure of the absolute accuracy of each intensity estimate. Table 3-7 displays the distribution of the deviations between analyzed C.I. number and the corresponding official intensity in terms of C.I. number. The table stratifies the results with respect to various tropical cyclone intensities. The right side of the table shows the percent of the analyzed intensity estimates that were less than and greater than the actual intensity--a measure of bias.

3.5.3.2. The cumulative distributions in Table 3-7 show that the intensity estimates of 90 percent of tropical storms and 85 percent of typhoons were within 1.0 C.I. number or 15 to 20 kt of the actual intensity. However, a small percentage of the estimates were as much as 35 kt in error. This magnitude of error is not unlike that which can occur when deriving intensity from minimum sea level pressure under certain conditions. The bias information in Table 3-7 indicates that the analysts underestimated about four times as many intensity estimates as they overestimated.

Table 3-7. Deviations of analyzed Current Intensity values from official best track intensity values.

Deviations (C.I.)		0	+0.5		+1.0		+1.5		+2.0		+2.5		+3.0		Bias	
Intensity	No. of Cases	% in Cat	% in Cat	Cum %	% in Cat	Cum %	% in Cat	Cum %	% in Cat	Cum %	% in Cat	Cum %	% in Cat	Cum %	% < Obs	% > Obs
< 65 kt	67	34	42	76	13	90	7	97	1	99	1	100	-	-	52	13
≥ 65 kt but < 85 kt	60	27	28	55	32	87	8	95	2	97	3	100	-	-	57	17
≥ 85 kt	57	28	40	58	26	82	11	93	7	100	-	-	-	-	70	12
All	184	27	37	64	23	86	9	95	3	98	2	100	-	-	59	14

3.5.3.3. Figures 3-14 through 3-17 illustrate the distribution of the deviations of the analysts' intensity estimates from those depicted by the best track for various tropical cyclone intensities. The mean absolute errors range from about 0.65 C.I. numbers for tropical storms (Figure 3-14) and stronger typhoons (Figure 3-16) to 0.82 for weaker typhoons (Figure 3-15). There is a substantial negative bias or underestimation of the intensity, especially for the weaker typhoons. Figure 3-17 shows that the average underestimation for storms of all intensities is 0.43 C.I. numbers or slightly less than one C.I. category.

3.6. Summary and Comparison with Other Studies. The gridding accuracies of the DMSP and NOAA polar orbiting satellites have improved considerably since the 1975 study of Sheets and Grieman. These improvements should provide satellite analysts and forecasters some increased confidence in locating tropical cyclones.

3.6.1. This study was based on a sample of erratically moving tropical cyclones from the western North Pacific during 1986. The methodology used in this study to determine internal consistency and absolute accuracy was expected to result in somewhat higher variations than results from other studies that used averaging schemes to determine the deviations. For the absolute accuracy of tropical storms, the deviations were about 25 percent higher than from other studies. As storms became more intense, the deviations approached those of other studies such as Martin (1988) and Sheets and McAdie (1988). Thus, the larger deviations for tropical storms cannot be attributed to the methodology alone. The internal consistency determinations were actually smaller than those in other studies for all tropical cyclone intensity ranges. These results indicate that the analysts are using very similar techniques to identify, position and track the tropical cyclones, even though the techniques may not accurately determine the actual tropical cyclone surface center. The experience level of the analyst proved to be a significant factor in both the internal consistency and absolute accuracy determinations. As expected, accuracy and internal consistency both improved with increasing tropical cyclone intensity.

3.6.2. A comparison of the absolute accuracy of positions derived from DMSP data versus those derived from NOAA data showed that the DMSP data provided about 10 percent better accuracy for tropical storms and typhoons as strong or stronger than 85 kt. However, for weaker typhoons, positions derived from NOAA data were about 7 percent more accurate. A similar comparison between positions derived from visible and infrared spectra data versus infrared data only, showed that positions made with visible spectra data were about 16 percent better for tropical storms and the stronger typhoons. For weaker typhoons, the improvement was less than 2 percent. It is not immediately clear why the weaker typhoons were less sensitive to the higher resolution data types than were tropical storms and stronger typhoons.

3.6.3. In measuring both absolute accuracy and internal consistency of intensity estimates, the study revealed that about 85 percent of the estimates were within 15 to 20 kt of each other and the actual intensity. However, occasional errors were as high as 35 kt with respect to absolute accuracy. The absolute deviations for both internal consistency and absolute

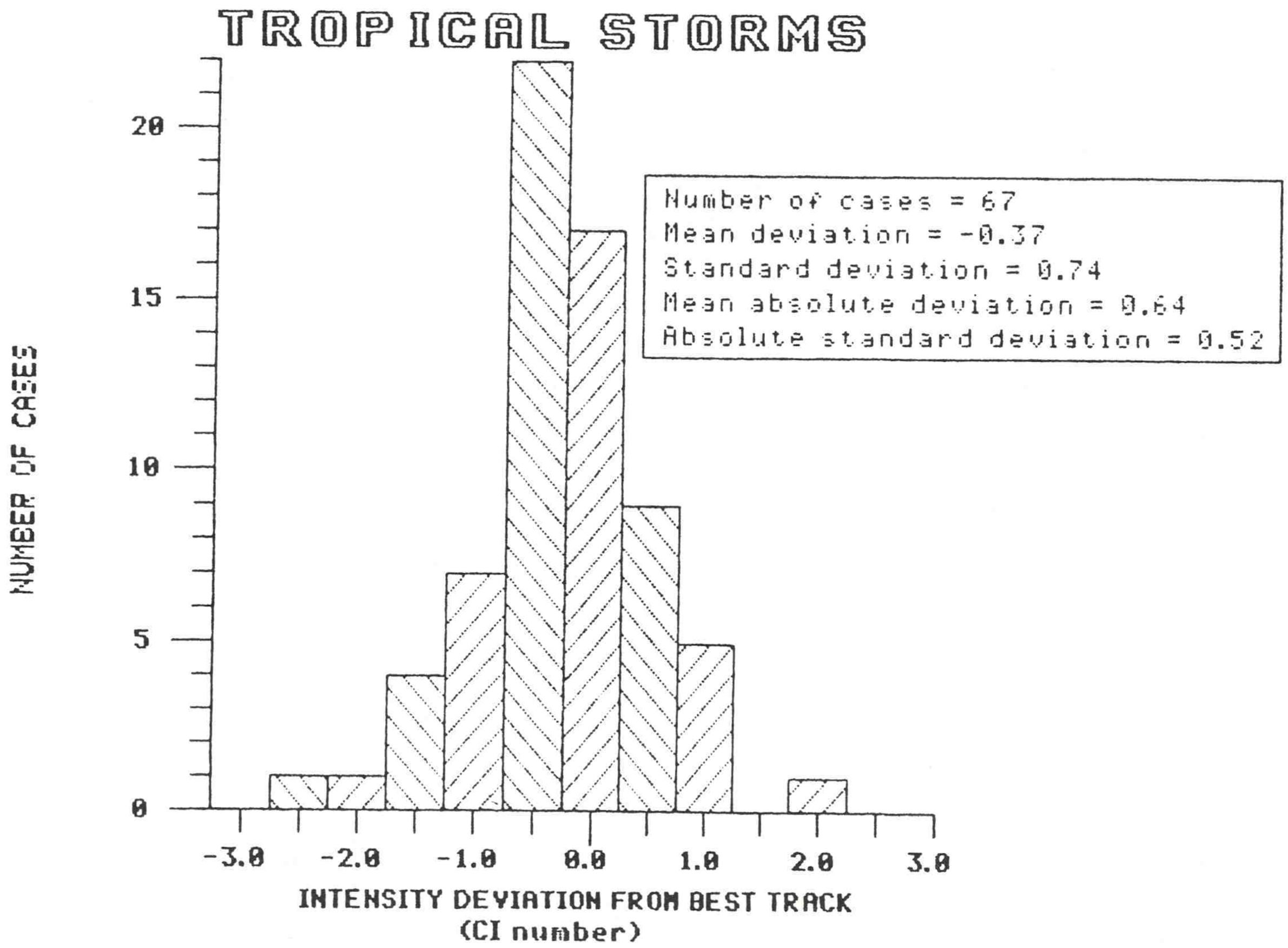


Figure 3-14. Deviations in C.I. numbers of intensities determined by all four analysts from the intensities determined from the best track for tropical storms.

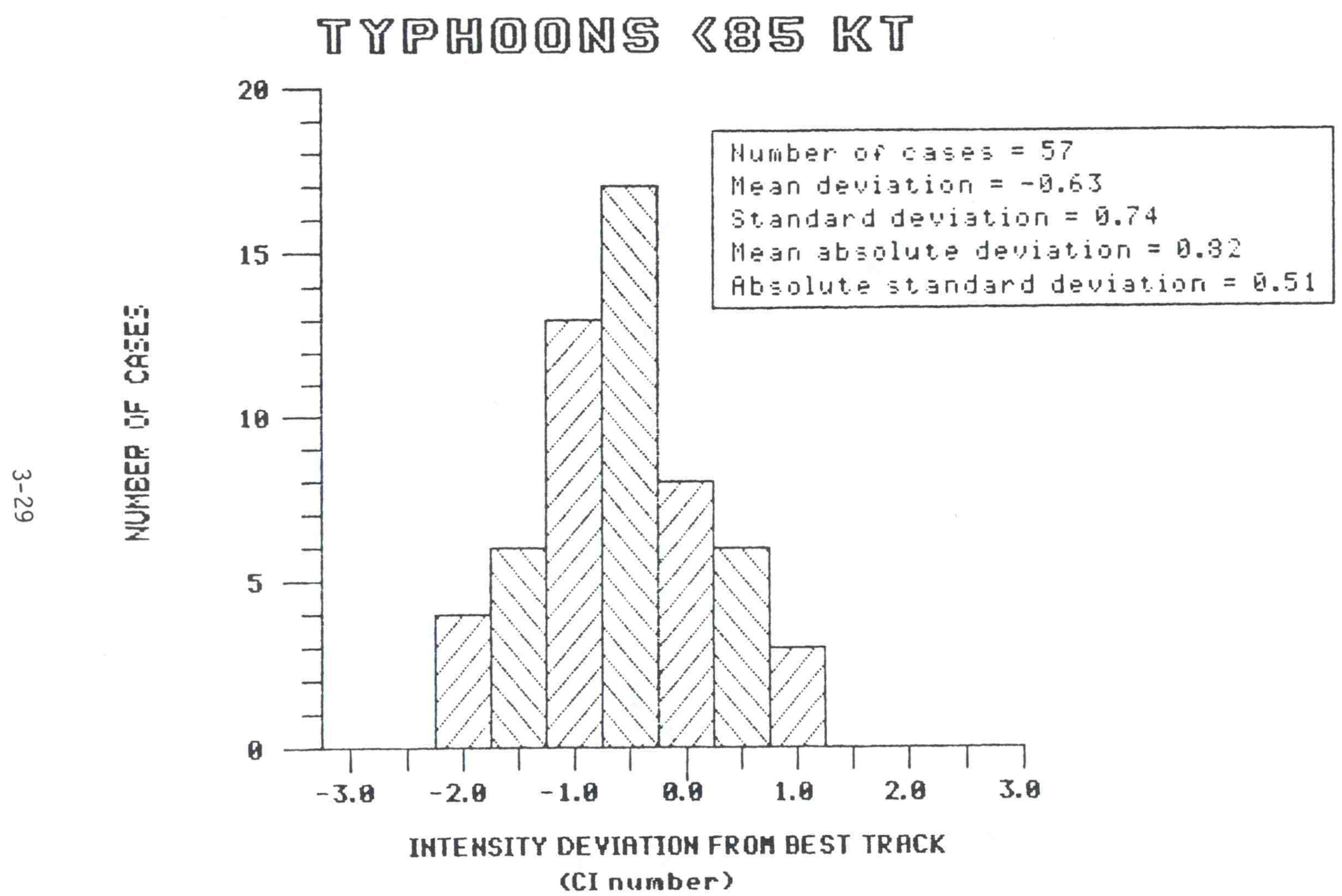


Figure 3-15. Deviations in C.I. numbers of intensities determined by all four analysts from the intensities determined from the best track for typhoons with intensities less than 85 kt.

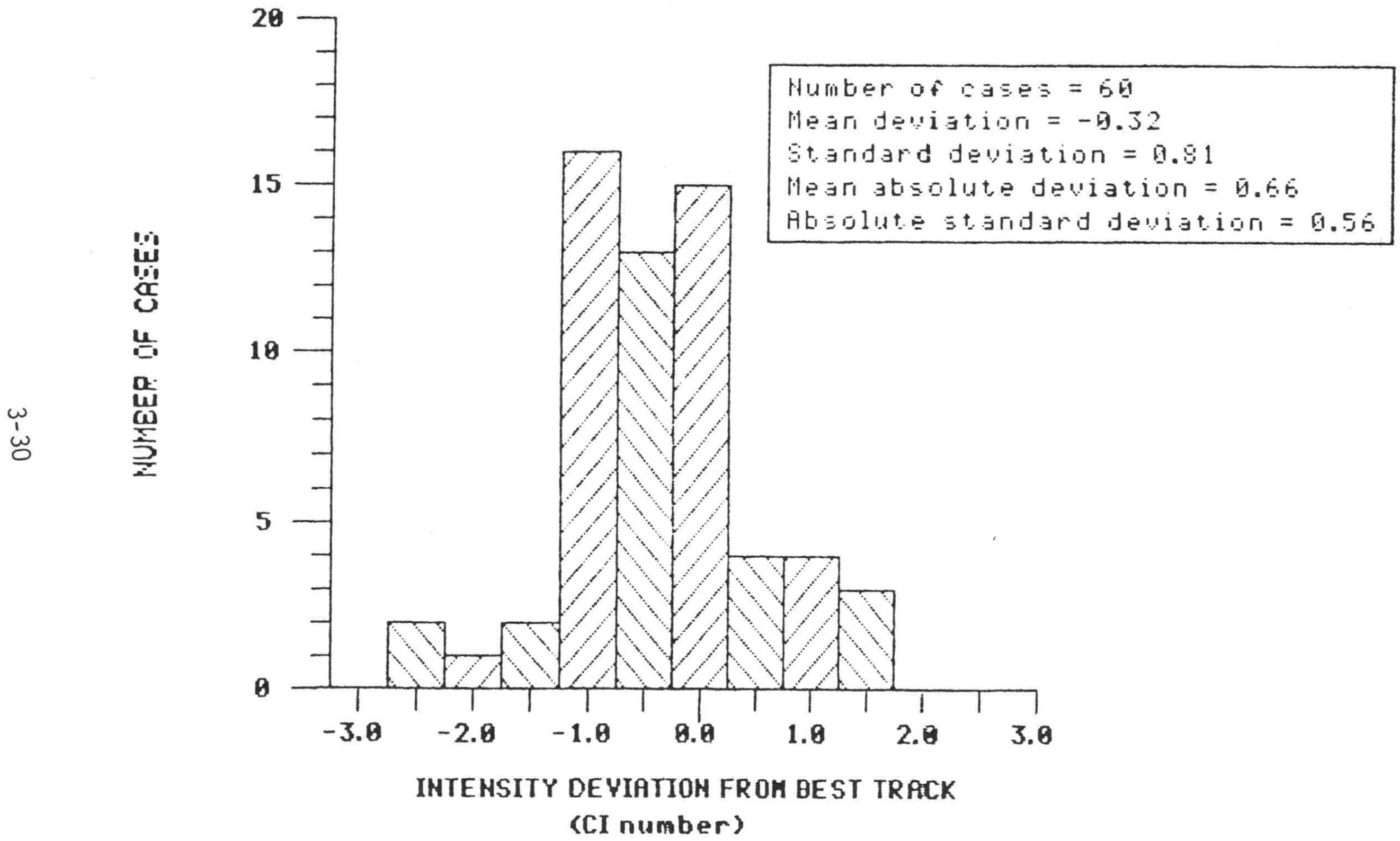


Figure 3-16. Deviations in C.I. numbers of intensities determined by all four analysts from the intensities determined from the best track for typhoons with intensities equal or greater than 85 kt.

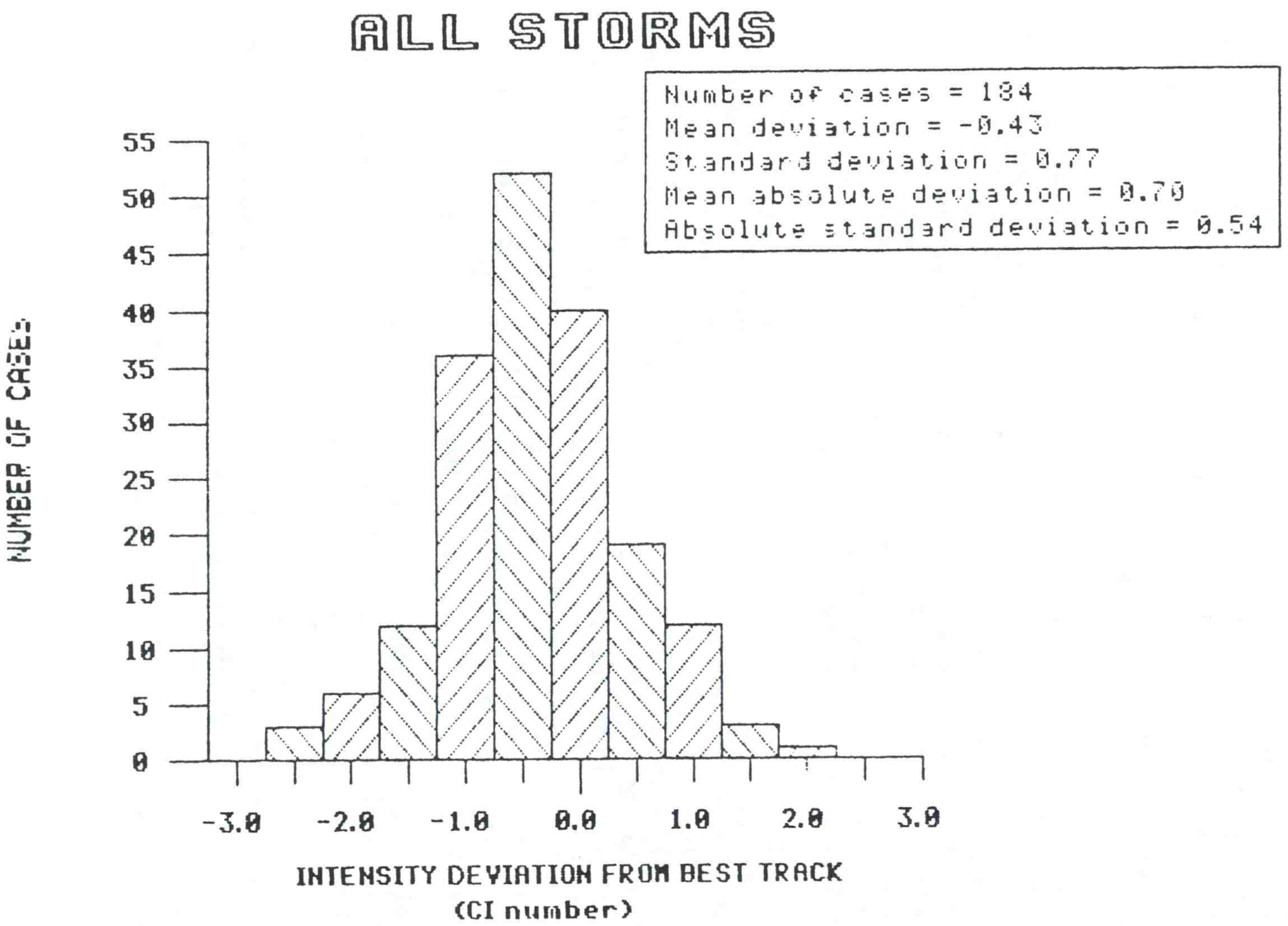


Figure 3-17. Deviations in C.I. numbers of intensities determined by all four analysts from the intensities determined from the best track for all tropical cyclones in this study.

accuracy ranged from about 0.65 to 0.80 C.I. numbers for the tropical cyclones. Tropical storms tended toward lower values while typhoons tended toward higher values. In looking at internal consistency, intensity deviations for tropical storms showed no bias, while deviations for typhoons showed a small negative bias or underestimate of intensity with respect to estimates made by the most experienced analyst. The biases associated with absolute accuracy were larger negative biases. In fact, four times as many intensity estimates were underestimated as were overestimated.

3.6.4. Studies by Gaby et al. (1980), Sheets and McAdie (1988), Mayfield, et al. (1988), and Dvorak (1987), show that positions derived from half-hourly animated geostationary satellite data are on average more accurate than those from 6-hourly polar-orbiting satellite data. Thus, if all possible polar orbiter data were used in the study, there is reason to assume that both the absolute accuracy and internal consistency of the polar orbiter positions would improve. Further, polar orbiters can detect drastic changes in low level tropical cyclone structure due to shear that geostationary satellites may not detect at night.

3.6.5. Improvements in tropical cyclone intensity estimates from satellite data are expected in the near future as refinements to the Dvorak technique come on line (Mr. Verne Dvorak and Mr. Ray Zehr, personal communication). In addition, the special sensor microware imager now flying on one DMSP satellite and programmed for all subsequent DMSP satellites, can penetrate cirrus clouds and locate tropical cyclone centers blocked to visual and infrared sensors. This capability should improve tropical cyclone positioning.

3.6.6. Several new studies addressing satellite accuracy have been performed. These studies need to be carefully compared with respect to the storm data samples and methodologies to put the results in perspective.

Acknowledgement. The author wishes to gratefully acknowledge the help of the tropical cyclone satellite analysts at the Air Force Global Weather Central who made the numerous satellite classifications, to Major Richard Langdon and Senior Master Sergeant Richard Hudson for gridding the data, and to the people at the Joint Typhoon Warning Center for selecting and compiling the imagery. This study would not have been possible without the hard work and dedication of them all. The author also greatly acknowledges the assistance of Mr. Ken Hill and Mr. Karl Zeller for their assimilation of the data, to Mr. George Taniguchi and Major Dennis Regan for reviewing the manuscript, and to Mrs. Helen Hutchison for typing the manuscript.

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PART 4

IMPACTS OF AIRCRAFT RECONNAISSANCE "FIXES" ON TROPICAL CYCLONE TRACK PREDICTIONS

by

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4.1. Introduction.

4.1.1. Nearly all tropical cyclone forecasters strongly believe that aircraft reconnaissance observations have major impacts upon tropical cyclone track and intensity predictions. These beliefs have primarily been based upon actual experiences, intuitive reasoning, and several studies that clearly demonstrated that aircraft reconnaissance observations substantially improve initial position and intensity estimates. Neumann, in an unpublished study, showed that after-the-fact "best track" inputs into a statistically-based climatology-persistence forecast model (CLIPER) resulted in substantial improvements (55, 32, 19, 11, and 4 percent, respectively for 12-, 24-, 36-, 48, and 72-hr forecasts) over operationally determined inputs. Sheets (1986) showed that through the use of an envelope approach for tracking of a hurricane, similar results could be obtained in real time using high-resolution pressure profile measurements. The key element in these processes was obtaining a good representation of the initial motion of the tropical cyclone. A logical extension of these arguments is that the more frequent observations were made, assuming reasonable accuracies, the better the chances of arriving at a reasonable representation of the initial motion. The Sheets technique is hypothesized to have a "built-in" filter that arrives at a smooth track for the tropical cyclone scale motion while other techniques require some arbitrary smoothing.

4.1.2. Although the great majority of tropical cyclone forecasters have felt that aircraft reconnaissance observations have strong and significant impacts upon tropical cyclone track predictions, these same forecasters felt that a quantitative demonstration of the impacts would be difficult.

That is, the forecasters felt that while this effect could be clearly demonstrated for several specific cases, a statistical demonstration of the impacts would be difficult using the operational data due to smoothing, data sampling biases, and the inability to isolate satellite-determined position estimates from aircraft reconnaissance observation influences. In spite of these real problems, a statistical assessment has now been made. The results of that assessment are summarized in Tables 4-1 and 4-2.

4.2. Data. Table 4-1 contains a tabulation of official forecast position errors for all Atlantic Basin tropical cyclones from 1980 through 1987. The forecast errors are stratified by latitude with sub-stratifications based upon the availability of aircraft reconnaissance position data within the 6-hr period prior to the forecast issuance time. Since there is usually a delay in transmitting observations, and forecasts are actually prepared approximately 30 min to 1 hr prior to issuance time, observations taken 45 min or later prior to the forecast issuance time were considered to be within the 6-hr period for the following forecast. These cases represent a small fraction of the total number of cases. Table 4-2 contains similar data stratified east and west of 75 degrees west for the middle latitude band.

4.3. Analysis.

4.3.1. Forecast errors are known to vary as a function of latitude. At low latitudes, hurricanes generally move from east to west in the trade wind belt. This is true for a large percentage of the cases well east of the Lesser Antilles. Forecast errors in these cases are generally quite small compared to higher latitude forecast errors. The result is that the low latitude sample probably underestimates the differences between satellite-based forecasts and the combination of satellite and aircraft reconnaissance-based forecasts. Since reconnaissance aircraft observations are generally only acquired west of 55 degrees west, they would contain a higher percentage of tropical cyclones moving northward compared to a sample well east of the islands where only satellite observations are available. Since more environmental data are available in the Caribbean area than east of the Lesser Antilles, this may partially offset the disadvantage of more northward moving systems that normally result in larger forecast errors.

4.3.2. The 12-hr forecast statistics for the sample of forecasts south of 20 degrees north indicate that substantial improvements in track forecasts are obtained when aircraft reconnaissance data are available. These improvements

average nearly 50 percent. Also, the number of big misses (errors greater than 100 nmi) are reduced by a factor of two. The results for the 24-hr forecasts for this latitudinal belt are not as dramatic. Here, only in the case where there was three or more reconnaissance observations available for the forecast was there a substantial improvement (21.4 percent and no large misses; i.e., cases with greater than 200 nmi errors). However, the sample for these cases is quite small and no strong conclusions can be drawn from these data. The fact that the aircraft-based sample contains more recurving cases than the satellite-based sample is probably the reason for the disparity between the 12-hr forecast results and the 24-hr forecast results. These same characteristics apparently carry over into the 48-hr and the 72-hr forecasts for this latitudinal belt.

4.3.3. The stratification sample for the latitudinal belt from 20 degrees north to 35 degrees north primarily contains the difficult recurvature forecast periods with some acceleration of forward speeds. Also, these are usually the more critical forecasts for land warning purposes. A probable bias in the sample that could favor the reconnaissance aircraft-based forecasts would be the presence of environmental data in the Caribbean and Gulf of Mexico. However, that favorable bias would probably be more than offset by looping storms due to interactions with systems over the continental United States. Examples of looping storms contained in the reconnaissance aircraft sample are the 1985 hurricanes Juan (three loops) and Elena as well as the unprecedented acceleration of Emily (1987) south of Bermuda that resulted in one 24-hr forecast error of more than 600 miles contained in the reconnaissance aircraft sample. Hortense (1984) also made some erratic turns, but the sample during this period was about evenly divided between reconnaissance and no-reconnaissance samples. Only Earl in 1986 contained a looping period that was totally contained in the no-reconnaissance sample.

4.3.4. The results of this sample clearly demonstrates the importance of aircraft reconnaissance information with more frequent "fixes" resulting in substantial improvements over those with less frequent fixes. The 12-hr forecast errors were reduced by 38.6 percent over the satellite-based forecasts when three or more reconnaissance fixes were available. Also, the number of large misses (errors greater than 100 nmi) was reduced by more than a factor of eight for this comparative sample. An average for all aircraft reconnaissance cases versus no-reconnaissance cases shows a 30-percent reduction in the forecast error and more than a

three-fold reduction in the number of large misses. The results for the 24-hr forecast errors are similar to that for the 12-hr forecast sample but slightly reduced. Here, the reduction in forecast error was 20 percent for all reconnaissance cases versus no-reconnaissance cases, and the number of large misses (forecast errors greater than 200 nmi) was reduced by a factor of three.

4.3.5. The differences for the 48- and 72-hr forecasts are surprisingly larger than anticipated based upon sensitivity tests of climatology and persistence type forecast models. The improvement ranges from 10 to 30 percent with the greatest improvements occurring with more frequent reconnaissance observations. These improvements are probably due to the forecaster's increased confidence in the accuracy of the initial motion. Early detection of some slight change in the direction or acceleration can have a significant impact upon the forecast 72 hr into the future. For instance, the detection of an acceleration of 1 or 2 kt can translate into a 4 to 5 kt acceleration in the forecast at the 48- to 72-hr forecast periods even with no difference in the assessment of the synoptic scale patterns. Another probable contribution to the increased improvement with more frequent fixes is that the majority of the three or more fixes per 6-hr period were obtained with the National Oceanic and Atmospheric Administration WP-3 aircraft with high-density data collection capability. Precise positioning was available using the inertial navigation systems, and entire data fields were available using satellite data links. The result is that the forecaster not only had increased confidence in intensity and wind field distributions, but also in the position and motion determinations for the tropical cyclone.

4.3.6. The differences for the 48- and 72-hr forecasts for reconnaissance and no-reconnaissance samples in the mid-latitude belt were so unexpectedly large that it was necessary to examine possible biases. As indicated earlier, one possible bias is the presence of more environmental data in the sample in regions of the Gulf of Mexico and the east coast of the United States. Another possible bias exists for storms that move inland over the Gulf Coast of the United States. Storms moving inland rapidly decrease in strength. Since verification statistics are only computed for tropical storm force or stronger systems, this would mean that the no-reconnaissance based sample likely contains more higher-latitude cases than the reconnaissance sample. This is probably not much of a factor for the 12- and 24-hr forecast cases but may result in an over-estimate of the differences

at 48- and 72-hr. However, as mentioned earlier, this bias is partially offset by the looping cases and other cases that experiencing interactions with stronger mid-latitude systems that are present over the open ocean. To estimate the influence of these factors, the data for the latitudinal belt from 20 degrees north to 35 degrees north was stratified into longitudinal belts east and west of 75 degrees west. The sample east of 75 degrees west would have similar data available for no-reconnaissance and reconnaissance cases. There would be no systematic cut off of storms at higher latitudes, and the availability of environmental data would be nearly equivalent for no reconnaissance and reconnaissance samples.

4.3.7. Table 4-2 shows the results of the longitudinal stratification. Note that for the sample east of 75 degrees west, there is a small increase in the forecast errors for essentially all categories at both 48- and 72-hr forecast periods compared to the total sample for this latitudinal belt. The differences indicate that indeed, the availability of environmental data had some impact upon forecast errors. However, the percentage improvement of reconnaissance over no-reconnaissance based forecasts still ranges from 15 to 24 percent at 48 hr and 12 to 32 percent at 72 hr. The 32 percent value is probably not representative because of the small sample involved. The all-reconnaissance categories represent a fairly large sample with average improvements of nearly 20 percent for 48-hr forecasts and 17 percent for 72-hr forecasts. All of these results are consistent with the results displayed in Table 4-1. The results for the sample west of 75 degrees west in this latitudinal belt, however, are not consistent with the results displayed in Table 4-1 or the sample east of 75 degrees west. Here the no-reconnaissance sample has substantially smaller errors at 48 hr than the reconnaissance samples. These cases primarily represent short periods of time between reconnaissance fixes and were probably for cases that were "well behaved" where satellite-based estimates were "calibrated" using reconnaissance fixes at 12-hr intervals. The likelihood that the no reconnaissance sample is non-representative is reflected by the errors at 48 hr being much below average. The number of cases is also reduced considerably for the no reconnaissance sample over that east of 75 degrees west and for all cases west of 75 degrees west for the 72-hr forecasts. The latter probably reflects the lack of verification at 72 hr for storms that have dissipated over the continental United States.

4.3.8. The sample for the latitudinal belt north of 35 degrees north is clearly biased in favor of the reconnaissance aircraft having lower errors. This is due to the fact that tropical cyclones accelerate toward the northeast at higher latitudes, and the total satellite sample likely contains more of these accelerated cases than the aircraft reconnaissance samples. However, there is a clear demonstration of reduced forecast errors for the 12- and 24-hr forecast periods when reconnaissance fixes are available. Due to the sample bias, the degree of that improvement is almost certainly over-estimated in this latitudinal belt. The sample for this latitudinal belt for the 48- and 72-hr forecast period to too small to draw any meaningful conclusions.

Table 4-1. Official forecast error statistics for the Atlantic Basin from 1980 through 1987. The data are stratified by latitude and by the availability of aircraft reconnaissance "fixes" within 6 hr prior to the forecast issuance time.

12-HR FORECASTS

	No. of cases	Mean (nmi)	Error Reduction versus No Recon		No. Cases > 100 nmi
<20° N					
No Recon	152	88.7	-	-	11
1 Recon	29	49.8	38.9	43.9	3
2 Recon	36	43.6	45.1	50.8	0
3+ Recon	7	43.3	45.4	51.2	0
All Recon	72	46.1	42.6	48.0	3
20°N to 35°N					
No Recon	297	66.5	-	-	49
1 Recon	82	53.9	12.6	18.9	4
2 Recon	151	46.0	20.5	30.8	9
3+ Recon	102	40.8	25.7	38.6	2
All Recon	335	46.4	20.1	30.2	15
>35°N					
No Recon	144	85.8	-	-	53
1 Recon	18	73.0	12.8	14.9	5
2 Recon	24	64.1	21.7	25.3	2
3+ Recon	10	48.8	37.0	43.1	1
All Recon	52	64.2	21.6	25.2	8

Table 4-1 (continued).

24-HR FORECASTS

	No. of cases	Mean (nmi)	Error Reduction versus No Recon		No. Cases > 100 nmi
<20° N					
No Recon	145	96.4	-	-	5
1 Recon	26	103.5	-6.9	-7.3	3
2 Recon	35	88.1	8.3	8.6	1
3+ Recon	6	75.8	20.6	21.4	0
All Recon	67	93.0	3.4	3.5	4
20°N to 35°N					
No Recon	276	133.5	-	-	44
1 Recon	75	118.9	14.6	10.9	6
2 Recon	141	104.7	18.8	21.6	10
3+ Recon	87	98.9	34.6	25.9	0
All Recon	303	106.6	26.9	20.1	16
>35°N					
No Recon	101	168.6	-	-	36
1 Recon	12	113.9	54.7	32.4	1
2 Recon	16	130.2	38.4	22.8	3
3+ Recon	10	145.3	23.3	13.8	3
All Recon	38	129.0	39.6	23.5	7

Table 4-1 (continued).

48-HR FORECASTS

	No. of cases	Mean (nmi)	Error Reduction versus No Recon		No. Cases > 100 nmi
<20° N					
No Recon	124	198.1	-	-	6
1 Recon	20	234.4	-36.3	-18.2	3
2 Recon	29	194.0	4.1	2.1	1
3+ Recon	6	150.0	48.1	24.3	0
All Recon	55	203.9	- 5.8	- 2.9	4
20°N to 35°N					
No Recon	220	292.4	-	-	58
1 Recon	57	256.1	36.3	12.4	8
2 Recon	106	218.1	74.3	25.4	13
3+ Recon	61	211.8	80.6	27.6	6
All Recon	224	226.1	66.3	22.7	27
>35°N					
No Recon	27	301.4	-	-	7
1 Recon	12	327.0	-25.6	- 8.5	3
2 Recon	2	137.5	163.9	54.4	0
3+ Recon	3	261.3	40.1	13.3	0
All Recon	17	293.1	8.1	2.7	3

Table 4-1 (continued).

72-HR FORECASTS

	No. of cases	Mean (nmi)	Error Reduction versus No Recon		No. Cases > 100 nmi
<20° N					
No Recon	95	315.1	-	-	9
1 Recon	16	425.3	-110.2	-35.0	2
2 Recon	26	348.2	- 33.1	-10.5	2
3+ Recon	5	236.2	78.9	25.0	0
All Recon	47	362.6	- 47.1	-14.9	4
20°N to 35°N					
No Recon	148	447.9	-	-	34
1 Recon	43	399.2	48.7	10.9	5
2 Recon	82	359.7	88.2	19.7	9
3+ Recon	37	302.6	145.3	32.4	2
All Recon	162	357.1	90.8	20.3	16
>35°N					
No Recon	4	488.0	-	-	2
1 Recon	7	386.7	101.3	20.8	0
2 Recon	2	257.0	231.0	48.8	0
3+ Recon	3	122.0	366.0	75.0	0
All Recon	12	278.6	209.4	42.9	0

Table 4-2. Official forecast error statistics for the Atlantic Basin from 1980 through 1987. The data are for the latitude belt of 20 to 35 degrees north and is stratified by longitude east or west of 75 degrees west and by the availability of aircraft reconnaissance "fixes" within 6 hr prior to the forecast issuance times.

48-HR FORECASTS

	No. of cases	Mean (nmi)	Error Reduction versus No Recon		No. Cases > 100 nmi
<75° W					
No Recon	188	304.4	-	-	47
1 Recon	45	256.8	47.6	15.6	6
2 Recon	62	237.7	66.7	21.9	10
3+ Recon	17	232.1	72.3	23.8	2
All Recon	124	243.9	60.5	19.9	18
>75° W					
No Recon	32	174.2	-	-	5
1 Recon	12	261.3	-87.1	-50.0	2
2 Recon	44	189.3	-15.1	- 8.7	3
3+ Recon	44	213.0	-38.8	-22.3	5
All Recon	100	208.2	-34.0	-19.5	10

72-HR FORECASTS

	No. of cases	Mean (nmi)	Error Reduction versus No Recon		No. Cases > 100 nmi
<75° W					
No Recon	128	462.3	-	-	31
1 Recon	39	407.3	55.0	11.9	6
2 Recon	54	379.8	82.5	17.8	8
3+ Recon	12	314.3	148.0	32.0	2
All Recon	105	382.8	79.5	17.2	16
>75° W					
No Recon	20	342.1	-	-	3
1 Recon	4	408.5	-66.4	-19.5	0
2 Recon	28	315.7	26.4	7.7	0
3+ Recon	25	305.3	36.8	10.8	0
All Recon	57	317.9	24.2	7.1	0

REFERENCE

1. Sheets, R.C. Hurricane Tracking Using an Envelope Approach--Impacts upon Forecasts. NOAA Technical Memorandum NWS/NHC 33. Miami, FL: NHC, 1986.

APPENDIX A

ABBREVIATIONS

AB	Air Base
AFGWC	Air Force Global Weather Central
ATS	Applications Technology Satellite
AWS	Air Weather Service
Cat	Category
C.I.	Current Intensity (Number)
CLIPER	Climatology-Persistence (forecast model)
Cum	Cumulative
DMSP	Defense Meteorological Satellite Program
EIR	Enhanced Infrared
EPHC	Eastern Pacific Hurricane Center
ESSA	Environmental Science Services Administration
FCM	Federal Coordinator for Meteorological Services and Supporting Research
GOES	Geostationary Operational Environmental Satellite
JTWC	Joint Typhoon Warning Center
NESS	National Environmental Satellite Service
NESDIS	National Environmental Satellite, Data, and Information Service
NHC	National Hurricane Center
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service
OFCM	Office of the Federal Coordinator for Meteorological Services and Supporting Research
SAB	Satellite Analysis Branch (NESDIS)
SD	Standard Deviation
USAF	United States Air Force
UTC	Universal Coordinated Time

APPENDIX B

SAFFIR-SIMPSON HURRICANE SCALE[1]

CATEGORY ONE HURRICANE

Winds[2]: 75-95 mph (65-82 kt) at standard anemometer elevations. F-scale is 1.0-1.4. Damage is primarily to shubbery, trees, foliage, and unanchored mobile homes. No real damage occurs to building structures. Some damage is done to poorly constructed signs.[3]

Storm Surge: Nominally is 4-5 ft (1.2-1.5 m) above normal. Low-lying coastal roads are inundated, minor pier damage occurs, some small craft in exposed anchorages break moorings.

CATEGORY TWO HURRICANE

Winds: 96-110 mph (83-95 kt) at standard anemometer elevations. F-scale is 1.5-1.9. Considerable damage is done to shrubbery and tree foliage, some trees are blown down. Major structural damage occurs to exposed mobile homes. Extensive damage occurs to poorly constructed signs. Some damage is done to roofing material, windows, and doors; no major damage occurs to building structures.

Storm Surge: Nominally is 6-8 ft (1.8-2.4 m) above normal. Coastal roads and low-lying escape routes inland are cut by rising water 2-4 hr before arrival of center. Considerable pier damage occurs, marinas are flooded. Small craft in unprotected anchorages break moorings. Evacuation of some shoreline residences and low-lying island areas is required.

CATEGORY THREE HURRICANE

Winds: 111-130 mph (96-113 kt) at standard anemometer elevations. F-scale is 2.0-2.4. Damage occurs to shrubbery and trees: foliage is blown off trees, large trees are blown down. Practically all poorly constructed signs are blown down, some roofing material damage occurs, some window and door damage occurs, and some structural damage occurs to

small residences and utility buildings. Mobile homes are destroyed. There is a minor amount of curtainwall failure.

Storm Surge: Nominally is 9-12 ft (2.7-3.7 m) above normal. Serious flooding occurs at the coast with many smaller structures near the coast destroyed. Larger structures are damaged by battering of floating debris. Low-lying escape routes inland are cut by rising water 3-5 hr before the center arrives. Terrain continuously lower than 5 ft (1.5 m) above sea level may be flooded inland 8 mi (12.9 m) or more. Evacuation of low-lying residences within several blocks of the shoreline may be required.

CATEGORY FOUR HURRICANE

Winds: 131-155 mph (114-135 kt) at standard anemometer elevations. F-scale is 2.5-2.9. Shrubs and trees are blown down, all signs are down. Extensive roofing material damage occurs, extensive window and door damage occurs, complete failure of roof structures occurs on many small residences, and complete destruction of mobile homes occurs. Some curtainwalls experience failure.

Storm Surge: Nominally is 13-18 ft (3.9-5.5 m) above normal. Terrain continuously lower than 10 ft (3 m) above sea level may be flooded inland as far as 6 mi (9.7 km). Major damage occurs to lower floors of structures near the shore due to flooding and battering action. Low-lying escape routes inland may be cut by rising water 3-5 hr before the storm center arrives. Major erosion of beach areas occurs. Massive evacuation of all residences within 500 yd (457 m) of the shoreline may be required and of single-story residences on low ground within 2 mi (3.2 km) of the shoreline.

CATEGORY FIVE HURRICANE

Winds: Greater than 155 mph (135 kt) at standard anemometer elevation. F-scale is 3.0 or greater. Shrubs and trees are down, roofing damage is considerable, all signs are down. Very severe and extensive window and door damage occurs. Complete failure of roof structures occurs on many residences and industrial buildings. Extensive glass failures occur, some complete buildings fail, small buildings are overturned and blown over or away, and complete destruction of mobile homes occurs.

Storm Surge: Height is nominally greater than 18 ft (5.5 m) above normal. Major damage occurs to lower floors of all structures located less than 15 ft (4.6 m) above sea level and within 500 yd (457 m) of the shoreline. Low-lying

escape routes inland are cut by rising water 3-5 hr before the storm center arrives.

Massive evacuations of residential areas situated on low ground within 5-10 mi (8-16 km) of the shoreline may be required.

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[1] The Saffir-Simpson Hurricane (SSH) Scale does not apply to the Pacific Islands.

[2] Definition of a sustained wind (from Fujita and Simpson, 1972). A sustained wind is one that persists for the minimum time period to establish optimal dynamic forces on a nominal building structure.

[3] T. Fujita, 1971: "Proposed Characteristics of Tornadoes and Hurricanes by Area and Intensity," University of Chicago (SMRP) Research Paper No. 91.

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