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TROPICAL CYCLONE OBSERVATION AND FORECASTING WITH AND WITHOUT AIRCRAFT RECONNAISSANCE

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ABSTRACT

This study attempts to better quantify the contribution of aircraft reconnaissance to the accuracy of Tropical Cyclone (TC) center fix, motion determination, and intensity estimates along with the impact on track forecasts. What is the impact on TC observations and forecasts when forecasters must rely only on weather satellites?

Analyses concentrate on differences in TC position-intensity and track forecasting which occur between periods when aircraft measurements were taken vs. periods when measurements were not made. Study is made of data from the Northwest Pacific for the period 1979-86. Over 200 TC cases with about 5,000 center position fixes are analyzed. Average and distributions of fix, motion, intensity, and forecast error differences between reconnaissance and non-reconnaissance periods are made. Differences also are examined with respect to satellite type and day-night measurements. Positioning and intensity estimate differences from simultaneous independent satellite measurements are studied as well.

Statistics are compared with other recent related studies. General agreement exists between these other studies. Results show that aircraft reconnaissance distinctly improves TC positioning, intensity estimation, and the short range TC forecast. Simultaneous independent satellite measurements of the same TC show that satellite analysts frequently have large differences in their fix estimates but not in their TC intensity estimates. Aircraft reconnaissance does not, on average, appear to improve the TC track forecast beyond 24 hours nor does it affect the conservative current 12-hour motion vector estimate. Recurvature forecasts are improved by having aircraft data, however.

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LIST OF SYMBOLS AND ACRONYMS

AIF = Aircraft Influence on TC Forecastss

AIR = Aircraft

AIR FLT WND = Aircraft Flight-Level Wind

AIR LAT = Aircraft Position Latitude

AIR LON = Aircraft Position Longitude

AIR SFC WND = Aircraft Estimated Surface Wind

AIR SLP = Aircraft Measured Sea-Level Pressure

AIR SPD = Aircraft Fix Derived Storm Motion Speed

AIR U = Aircraft Fix Derived U Component of Storm Motion

AIR V = Aircraft Fix Derived V Component of Storm Motion

ATCR = Annual Tropical Cyclone Report

CI = Current Intensity

CI MAX = Maximum Estimated Current Intensity

CI MIN = Minimum Estimated Current Intensity

CLIPER = Climatology-Persistence Track Forecast Model

CLO = Closest Actual Observation To An Interpolated Data Point

CLS = Highest Intensity Classification That A Tropical Cyclone Achieved

CSU = Colorado State University

DIST = Distance

DMSP = Defense Meteorological Satellite Program

IMG = Imagery Type

INT = Interval Length Between Actual Aircraft Measurements

IR = Infrared

JTWC = Joint Typhoon Warning Center

LAT DIFF = Latitudinal Difference

LON DIFF = Longitudinal Difference

NBR = Number Of Obervations

NE = Northeast

NEPRF = Naval Environmental Prediction Research Facility

NW = Northwest

OTCM = One-Way (Interactive) Tropical Cyclone Model

PABT = Post-Analysis Best Track

PABT LAT = Post-Analysis Best Track Derived Latitude

PABT LON = Post-Analysis Best Track Derived Longitude

PABT WND = Post-Analysis Best Track Estimate For Wind Speed

PCT = Percent Of Interval Used For Interpolation

SAMC = Satellite and Aircraft Measurement Comparison

SAT CI = Satellite Estimated Current Intensity

SAT LAT = Satellite Derived Estimate For TC Position Latitude

SAT LON = Satellite Derived Estimate For TC Position Longitude

SAT NAME = Name of Satellite Used For Measurement Data

SAT SFC WND = Satellite Derived Estimate For Surface Wind

SAT SLP = Satellite Derived Estimate For TC Minimum Sea-Level Pressure

SAT SPD = Satellite Fix Derived Estimate For Storm Motion Speed

SAT U = Satellite Fix Estimate For U Component of Storm Motion

SAT V = Satellite Fix Estimate For V Component of Storm Motion

SISO = Simultaneous Independent Satellite Observations

SLP = Sea-Level Pressure

SLP DIFF = Difference In Sea-Level Pressure Estimates

SPD DIFF = Difference In Storm Motion Speed Estimates

ST = Super-Typhoon (Also Abbreviated STY)

SUN = Variable For Day-Night Determination

TC = Tropical Cyclone

TC NBR = Tropical Cyclone Number

TD = Tropical Depression

TRK = Storm Track Classification

TS = Tropical Storm

TY/HURR = Typhoon Or Hurricane

U DIFF = Difference In U Component Of Storm Motion

V DIFF = Difference In V Component Of Storm Motion

VIS = Visible Visual Satellite Imagery

WBT = Working Best Track

WND DIFF = Wind Speed Estimate Difference

WRG WND = JTWC Warning Position Maximum Wind

Chapter 1

INTRODUCTION

This study attempts to clarify the technical question of how much aircraft reconnaissance improves Tropical Cyclone (TC) observation and forecasting beyond what is provided by current weather satellite technology. The reconnaissance aircraft directly measures TC position and intensity while the satellite gives image information from which position and intensity must be judiciously inferred. Analyses are made of NW Pacific TC fix position, motion, intensity, and forecast track error as measured by satellite, aircraft, and their combination. We try to ascertain the extent to which satellite data may be employed independently of aircraft measurements for tropical cyclone observation and forecasting. Can satellites, without supplemental aircraft information, provide a sufficient measurement capability for monitoring and forecasting tropical cyclones?

The motivation for this study has been the discontinuance of TC aircraft reconnaissance in the NW Pacific in 1987. The termination of aircraft reconnaissance in this region has raised general questions as to how well TC observation and forecasting can be accomplished without supporting reconnaissance aircraft. Pertinent questions have also arisen regarding potential elimination of Atlantic–basin military TC reconnaissance. In addition, a number of foreign countries have discussed, or are now discussing, the desirability of establishing regional TC reconnaissance programs. Are these reconnaissance proposals justified on technical grounds?

This study does not attempt an economic or political judgment as to the desirability of having aircraft reconnaissance. We only try to determine areas of confidence and caution for those who must make TC forecasts without the support of dedicated aircraft measurements. Seemingly, the more TC forecasters know about the contribution of aircraft reconnaissance, the better they should be at making future forecast decisions based primarily from the satellite. This study also hopefully gives beneficial background information to decision makers who must implement reconnaissance resources in the Atlantic—the only basin where routine reconnaissance flights are still made. We compare our results with related studies on this subject by Sheets and McAdie (1988) and McBride and Holland (1987).

The central question is how accurate the current and near future satellites are for specifying TC position, motion, and intensity without support from aerial reconnaissance. Many TC specialists feel that this is an unresolved question which needs careful analysis. Most TC satellite fix and intensity estimates in the NW Pacific and Atlantic have not been made independently of aircraft information. When reconnaissance flights were not made, ground-truth information was typically not available to verify satellite TC measurement accuracy. A long running debate has been ongoing between satellite TC specialists and operational forecasters over the accuracy and reliability of satellite TC estimates. This question deserves more thorough study.

Satellite measurement technology and analysis techniques have been evolving. The ability of the satellites to monitor TC activity in the 1970's may not be comparable to abilities present in the early to mid 1980's. Thus, the period of our analysis was limited to the more recent years of 1979 through 1986. This chronological restriction ensures that results are based on relatively recent satellite technologies and image interpretation techniques. Only the Northwest Pacific basin was studied in detail. The NW Pacific has the highest incidence of TCs and the largest TC data sets. For comparison, other relevant recent studies on this subject have also been scrutinized and are compared with results from this study.

Three basic types of comparative data analysis are made.

1. Satellite and Aircraft Measurement Comparison (SAMC). A comparison is made of the differences between corresponding satellite and aircraft measurements with regard to center fix, motion, and intensity. Aircraft information has been

time-interpolated to satellite fix periods. How different is satellite determined information? Even though these data are typically not independent, important inferences on the impact of aircraft probably can be drawn.

2. Simultaneous Independent Satellite Observations (SISO). Cases of operational sites that independently fixed a TC's position and intensity, at the same time, are studied. This indicates how consistent independent satellite fix and intensity estimates are.

3. Aircraft Influence on TC Forecasts (AIF). This analysis determined the differences in 24-, 48-, and 72-hour forecast errors for TCs which had reconnaissance data in the 12 hours before a forecast vs. those forecast situations in which aircraft information was not available.

Chapter 2

THE RESEARCH DATA SET

2.1 Data sources

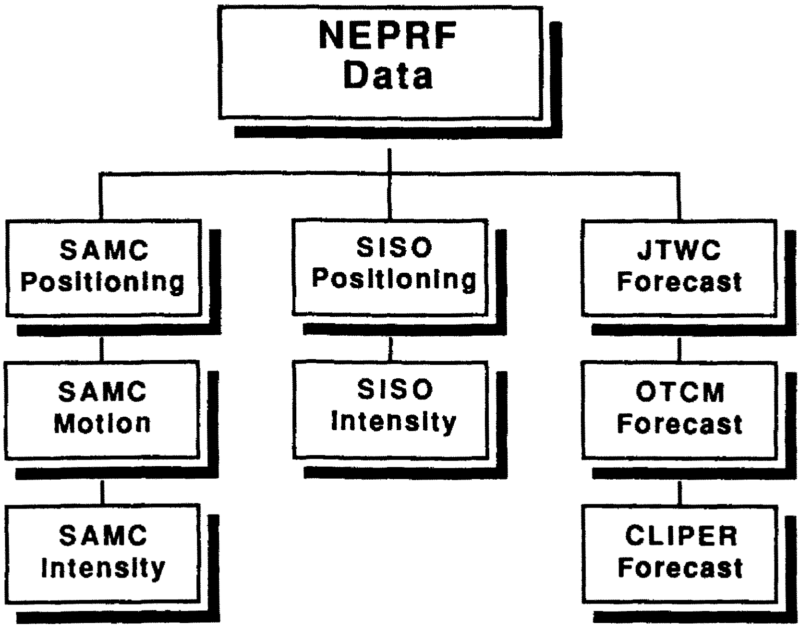
Tropical cyclone (TC) track statistics have been supplied by the Naval Environmental Prediction Research Facility (NEPRF). (Information is more extensive than that listed by the Guam Annual Tropical Cyclone Reports (ATCR), published by the Joint Typhoon Warning Center (JTWC).) These data contain fix information determined by satellite and aircraft. Also included are 6-hourly operational working track, post-analysis best track fix and intensity information together with different forecast verification data. NEPRF scientists, Ted Tsui and Ron Miller, are responsible for this detailed TC information. The data were provided on magnetic tape for transfer into a Colorado State University (CSU) mainframe computer.

2.2 Data processing techniques

All TC data were transferred from the CSU mainframe computer into subsets for specific topic investigation. Each data subset was designed for analysis on a micro-computer. Figure 2.1 depicts the flow and processing of information into the various data subsets. Appendix A provides a reference to the hardware and software configuration used for this study.

2.3 Data set structure

Data were imported into a micro-computer in a spreadsheet, or matrix, format. In this case, each column represents a unique variable and each row a discrete observation or event with respect to time. Appendix B gives a quick reference to the variables (columns in



NEPRF - Naval Environmental Prediction Research Facility
SAMC - Satellite and Aircraft Measurement Comparison
SISO - Simultaneous Independent Satellite Observations
JTWC - Joint Typhoon Warning Center
CLIPER - Climatology-Persistence Model
OTCM - One-Way Tropical Cyclone Model

Figure 2.1: Schematic outline of basic data subsets which are used for analysis. Box defines acronyms.

the spreadsheet) included in each of the data subsets. Several items were treated similarly in each data subset. The TC name, TC index number, date and time groups, day-night determination, satellite type (DMSP, NOAA, GMS, etc.) and the image class (Visual, IR, or both) were included in all of the data sets.

2.4 Position interpolation

Tropical cyclone tracks were objectively specified from individual aircraft determined TC positions using an Akima (1970) interpolation scheme. Recent year aircraft fixes using Omega-LORAN and Doppler navigation were assumed sufficiently accurate for use as a ground-truth for track determination. Navigational fix errors and meteorological errors such as eye center or center of closed circulation, were thus assumed significantly smaller when measured by regular twice-a-day aircraft missions (2 fixes per mission) than were those fix measured by the satellite. It is recognized that the aircraft fix accuracy is also not precise. Although aircraft fixes can occasionally be inaccurate, they were with the navigation equipment on the aircraft generally much superior to the satellite fix observations. Aircraft measurements of the storm's minimum central sea-level pressure were also assumed to be accurate. Aircraft central pressure accuracy is known to be quite reliable.

Satellite fixes were compared to corresponding interpolated aircraft tracks. Care was taken in any aircraft interpolation over longer periods. In general, there were two aircraft missions each day with four aircraft fixes or about one aircraft fix every 4 to 8 hours. We believe that this is sufficient to plot a reasonably accurate aircraft-only determined TC track. We recognize, however, that for TC undergoing short period oscillatory or looping motion that these aircraft fixes may not give representative longer period track trajectories.

Figure 2.2 gives an example of our interpolation of aircraft positions to form a track for a TC that is moving from southeast to northwest. Both satellite and aircraft fixes are plotted. Aircraft fixes are not at the same time as the satellite data and must be time-interpolated for comparison to satellite fixes. A gray line indicates the interpolated

TC path from the aircraft data. Square black dots indicate interpolated aircraft data at the time of comparison. Boxes are drawn around the collection of comparison points. One box, at time 2, includes two satellite fixes. This is a case of Simultaneous Independent Satellite Observations (SISO)–two different satellite receiving sites have independently fixed the TC's position and intensity at the same time but at different positions. Figure 2.3 illustrates the SISO process. Differences in independent position and intensity fixes will be analyzed in considerable detail.

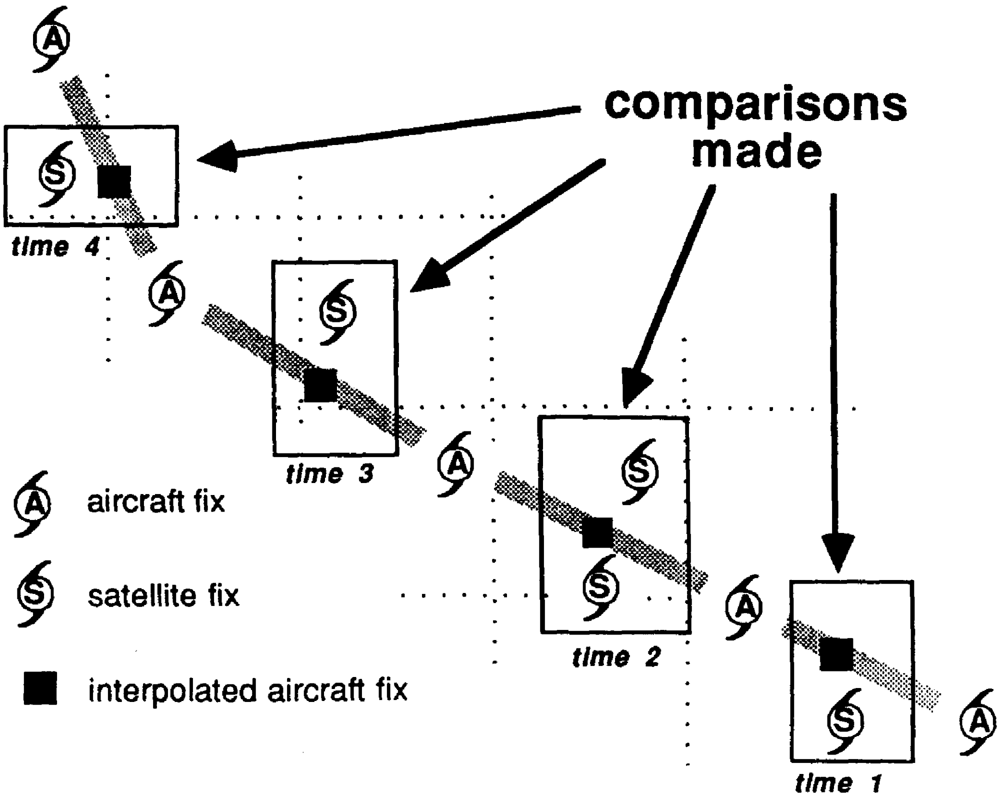


Figure 2.2: Typical satellite and aircraft fixes for a tropical cyclone moving towards the northwest. Small black squares are aircraft data interpolated to satellite fix times. The aircraft interpolation path is along the thick gray-shade line. Satellite and Aircraft Measurement Comparison (SAMC) data is collected at each satellite time—boxes are drawn around data comparisons. Time 2 illustrates two Simultaneous Independent Satellite Observations (SISO) of a TC fix.

Simultaneous satellite observations came primarily from six operational sites: the Joint Typhoon Warning Center (Guam), Air Force Global Weather Center (Omaha, NE)

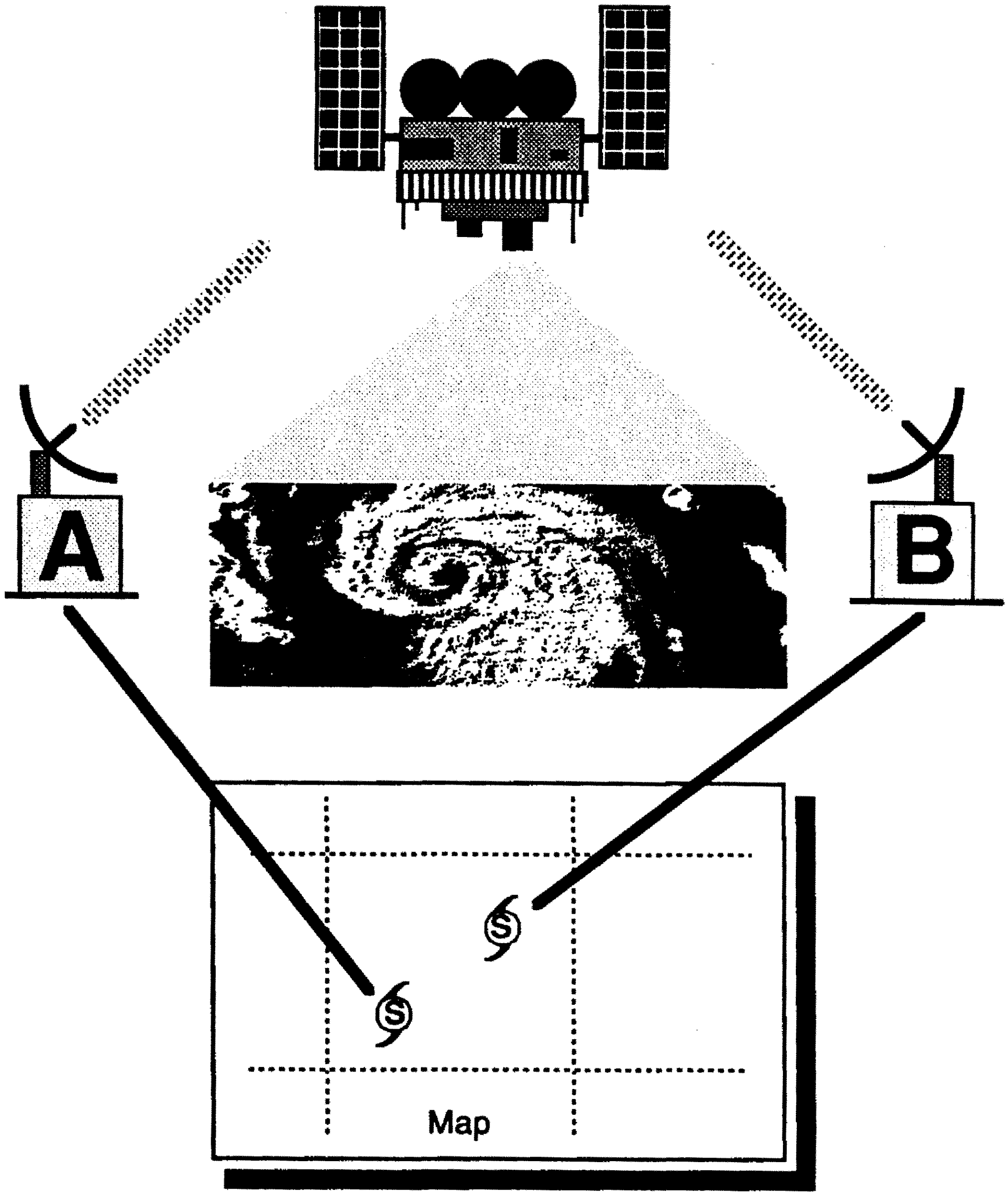


Figure 2.3: An illustration of Simultaneous Independent Satellite Observations (SISO). A satellite observes the tropical cyclone and two sites (A and B) receive and process the imagery information, simultaneously. This illustrates how simultaneous independent satellite fixes do not necessarily coincide with each other.

and from other military sites in the Philippines, Okinawa, Korea, and Hawaii. A careful study of the SISO fix and intensity differences between different stations did not show any obvious systematic biases between the various combinations of simultaneous observations. Operational analysts changed frequently at each of the sites during the 1979-86 period of study, so little site-specific influences were expected or were detected.

To monitor the time interpolation between aircraft fixes, the interval of the interpolation and the percentage of the time interval necessary to reach the aircraft track interpolation point was recorded. In addition, the time from the satellite position time to the nearest aircraft position fix was also included. Figure 2.4 is an example of how these time interpolation variables are derived.

2.5 Satellite and aircraft measurement comparison (SAMC) of TC positioning, motion, and intensity

Even though the satellite fixes often are not independent of the aircraft positions, a separation of this dependence is virtually impossible. Despite this lack of independence, general information on the reliability of the satellite measurements can be gleaned from these comparisons.

The latitude and longitude of the TC vortex fix by the satellite were compared with the time interpolated latitude and longitude of the aircraft data. Differences were output and a total fix difference distance calculated by using rectilinear or mercator map geometry.

Satellite and aircraft derived U (east-west) and V (north-south) components of TC motion were also calculated. Individual satellite and aircraft speed and directional or vector differences were then determined.

The Dvorak Current Intensity Number (CI) (Dvorak, 1984) is reported for each satellite observation and included in the analysis. Although this satellite CI determination is frequently known not to be independent of the aircraft measurement, this comparison nevertheless offers some insight into the reliability of satellite intensity estimates.

In addition to the Dvorak (1984) Current Intensity (CI), derived from the satellite, aircraft measured TC intensity was obtained. A linear time-interpolation was used to

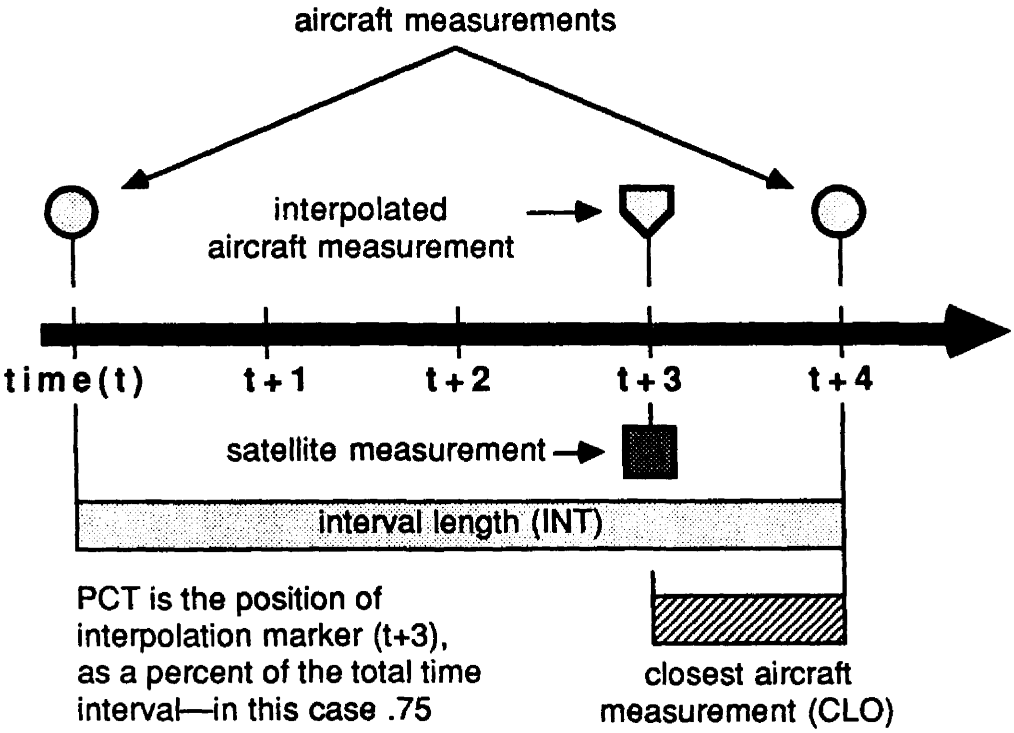


Figure 2.4: Illustration of the method of time interpolating of aircraft track position and intensity to satellite position times for fix and intensity comparisons. Aircraft measurements were made at times t and t+4. Aircraft fix data were interpolated to the satellite fix time at t+3. The total interval length from t to t+4 is recorded in the data set along with the time interval from the interpolated point at t+3, the closest aircraft measurement at t+4. The position of the interpolation is recorded as a percentage (PCT) of the total interval length.

derive the aircraft intensity measure for comparison at each satellite fix time. The CI was converted directly to a representative minimum sea-level pressure (SLP) and maximum surface wind for comparison to the aircraft time-interpolated measurements. The satellite derived sea-level minimum central pressure was compared with the aircraft measured minimum central pressure.

2.6 Simultaneous Independent Satellite Observations (SISO) of TC position and intensity

A second class of calculations involved simultaneous independent satellite TC fix and intensity estimates. Many situations are available where two operational satellite analysis sites made simultaneous and independent measurements of a TC's position and intensity. Analyses were made of these differences. Also noted was whether or not an aircraft center fix had been taken in the 12 hours prior to the Simultaneous Independent Satellite Observation (SISO). These measurements appear to be very valuable in showing the degree of satellite consistency between separate and independent satellite analysts and in throwing light on how well the satellite can measure TC position and intensity without aircraft support.

2.7 Aircraft influence on track forecasts (AIF)

A third basic data set was assembled to study the degree to which prior 6- or 12-hour aircraft fixes may influence 24- to 72-hr TC track forecasts. Are track forecasts of TCs which had prior aircraft reconnaissance any better than forecasts of TCs without reconnaissance data?

Post-analysis best track positions were used to verify forecasts. All forecast track differences were computed using a great-circle algorithm. Forecast results were stratified by whether aircraft reconnaissance was available in the 12-hour interval or in the 6-hour interval prior to the forecast initialization time. In addition, reconnaissance influences on TC track forecasts were selectively stratified by the overall TC motion characteristics of recurver, straight-mover, or odd-mover.

2.8 Characteristics of each data set

Table 2.1 lists the characteristics of the data which went into the Satellite and Aircraft Measurement Comparison (SAMC) study. Enough data is available in this sample to obtain insights as to how satellite observations compare with the more reliable aircraft measurements even though a large percentage of the satellite measurements were not taken independently of the aircraft data.

Table 2.2 presents characteristics of the Simultaneous Independent Satellite Observations (SISO) data. This is a somewhat smaller data set and does not include enough time continuity to allow the study of TC motion. However, positioning and intensity estimate differences have been scrutinized.

The third basic data set involves an analysis of how having aircraft reconnaissance, or not having aircraft reconnaissance, might influence the 24- to 72-hr forecasts. This study is designated Aircraft Influence on Track Forecasts (AIF). Table 2.3 is an initial reference to the data available in this data set. Note the sizable amount of forecast data available for situations where aircraft were or were not available in the previous 6- and 12-hr forecast period. The operational JTWC forecast is studied along with verifications of the OTCM and the CLIPER forecast models. These analyses are directed toward a determination of the extent aircraft reconnaissance fixes may improve the 24-, 48-, and 72-hr TC track forecasts.

Table 2.1: Characteristics of the Satellite and Aircraft Measurement Comparison (SAMC) data set.

SAMC Data

Size	Period of Study	Day-Night	Image Type	Satellites	TC Intensity
7893 satellite observations 4594 satellite obs within ±3 hrs of aircraft measurement	1980 - 1986	72% day 28% night	53% IR 13% VIS 34% both	25% DMSP 28% NOAA 47% GMS	27% CI 1 - 3 62% CI 3.5-5.5 11% CI 6 - 8

Table 2.2: Characteristics of the Simultaneous Independent Satellite Observations (SISO) data set.

SISO Data

Size	2906 SISO events
Period of Study	1979 - 1986
Image Type	35% IR 13% VIS 52% both
Day-Night	69% day 31% night
TC Intensity	39% CI 1 - 3 52% CI 3.5-5.5 9% CI 6 - 8
Satellites	54% DMSP 39% NOAA 5% GMS
Aircraft fix 12 hrs before SISO	63% of cases

Table 2.3: Characteristics of the Aircraft Influence on Track Forecasts (AIF) data set.

AIF data	
Period of Study	1979 - 1986
Aircraft fix 6 hrs before forecast	42% of cases
Aircraft fix 12 hrs before forecast	68% of cases
Size	warning position vs. best track 4883 cases
	JTWC forecasts 24hr - 4123 48hr - 3204 72hr - 2397
	CLIPER forecasts 24hr - 3228 48hr - 2662 72hr - 2110
	OTCM forecasts 24hr - 2704 48hr - 2159 72hr - 1544
TC Intensity	TC maximum wind 45 knots or less in 30% of cases

Chapter 3

THE PROBLEM OF SATELLITE OBSERVATION BIAS FROM AIRCRAFT DATA

Aircraft data bias is defined as the unavoidable influence of aircraft measurements upon the satellite determined TC fix or intensity estimation. Aircraft bias is as inherent part of operational satellite fixes and intensity estimates when aircraft and satellite data are jointly utilized.

Persistence usually plays a major role in operational TC fix and intensity estimates. Most fix or intensity estimates are influenced by recent past observations. This presents a major problem for anyone trying to determine where the satellite fixes might have been located, or how TC intensity may have been estimated via the satellite, had aircraft information not been available to help guide the fix and intensity determinations. In the operational environment, all data sources are continually monitored in order to develop the most accurate working best track and intensity estimate. This working best track and intensity estimation usually has inherent biases between the aircraft and satellite. Satellite analysts use aircraft reconnaissance data to assist in their assessment of TC fix and TC intensity estimates for best quality analysis and forecasts. However, the aircraft typically biases the satellite measurement to a much larger degree than the satellite may bias the aircraft measurement. For instance, a forecaster would usually not move an aircraft determined fix position to conform to the fix position determined from a satellite analyst.

Truly unbiased satellite measurements are those made without any inference from aircraft or other measurement sources such as land-based radar. But an independent verification of the accuracy of the satellite measurements require these same observations.

Objective separation of the influence of prior aircraft information on satellite fix and intensity is virtually impossible. Single satellite observations cannot be examined out of the context of the prior time-sequence of TC fix and intensity information. Judgement calls and inherent subjectivity always exist. No two satellite analysts use aircraft data or their past satellite information in the same way. The aircraft data often comes sporadically and has varying impact on the satellite TC estimates for different situations.

Simultaneous Independent Satellite Observations (SISO) appear as a major tool to help evaluate this aircraft bias on satellite data and to determine how accurate the satellite fix estimates would have been without the support of the aircraft. The degree of positioning scatter of simultaneous independent satellite differences is perhaps the best way to evaluate the satellite's positioning fix capability.

About 3,000 SISO positioning fix comparison cases were separated into two groups: those simultaneous satellite positioning fixes that occurred when an aircraft had fixed the TC's center and intensity within 12 hours prior to the SISO comparison and those situations when no aircraft reconnaissance measurements were made in the 12-hour period before the SISO evaluation.

Figure 3.1 shows the mean and standard deviation for the two stratifications. The group without the aircraft measurements has a 30 percent larger mean and standard deviation of positioning differences than the group with aircraft measurements. Evidence is thus strong that satellite analysts were using aircraft information to improve their fix estimates.

Note that independent satellite fixes without prior aircraft data are, on average, 34 n mi or a half degree latitude different from each other.

Also note that about 15 percent of those independent satellite fixes are in error by more than one degree. By contrast, one would expect positioning differences of only a few miles if two reconnaissance aircraft could both simultaneously and independently fix the TC center. SISO does not appear as a good measure of the satellite's TC intensity estimate accuracy, however.

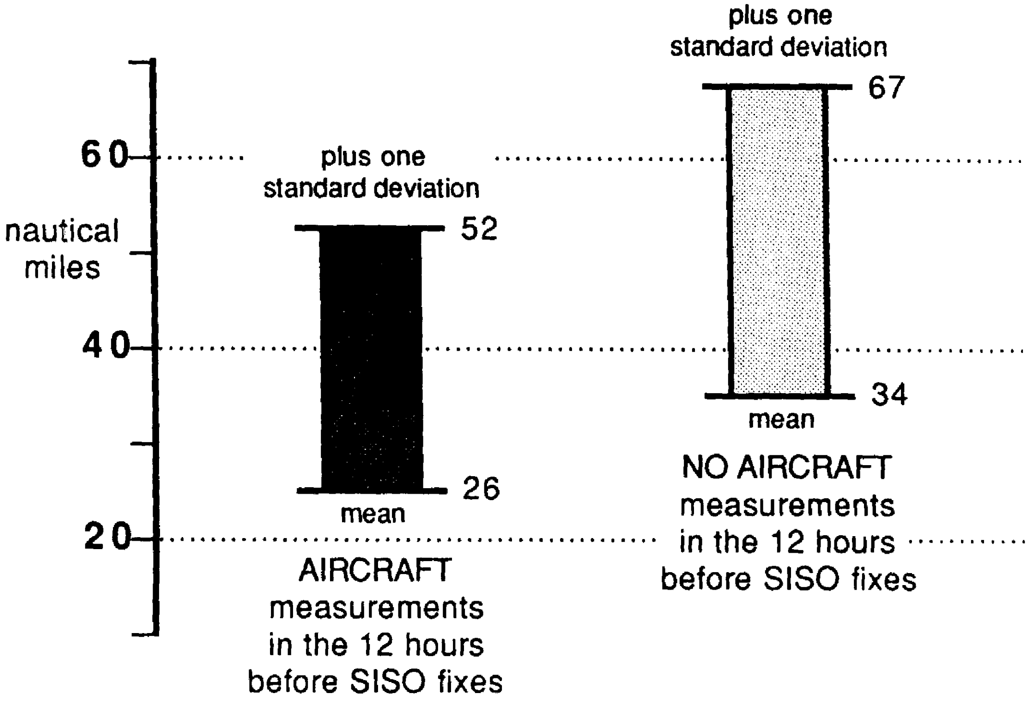


Figure 3.1: Comparison of mean and one standard deviation of fix position difference from Simultaneous Independent Satellite Observations (SISO). Diagram on the left shows fix difference when reconnaissance aircraft were present within 12 hours prior to the satellite fix times; diagram on the right gives information when no aircraft were available within 12 hours of fix time.

The impact of aircraft reconnaissance biases on satellite estimates of TC intensity are found to be more complicated. These biases are discussed in Chapter 6.

Chapter 4

TROPICAL CYCLONE POSITIONING DIFFERENCES

4.1 Distribution of TC positioning differences

Tropical cyclone fix and intensity estimate differences between aircraft and satellites are now selectively analyzed knowing that some degree of aircraft-induced bias in the satellite measurements is often a contaminant.

Satellite and aircraft often will report different TC fix positions at about the same time (say within 3 hours of each other). Figure 4.1 shows the distribution of Satellite and Aircraft Measurement Comparison (SAMC) position differences. Aircraft fix positions within 3 hours of the satellite fix are time-interpolated to correspond to satellite fix times. The position differences in Fig. 4.1 include all intensities. Note that position fixes can frequently vary by over 50 n mi. The Simultaneous Independent Satellite Observations (SISO) data of position fix differences are also shown in the same manner in Fig. 4.2.

In both analyses a number of large position differences are present. Table 4.1 shows the mean, standard deviation, 10th percentile, 90th percentile, and 10th to 90th percentile range for TC positioning differences from both SAMC and the SISO data. Although both analysis methods yielded similar results, SISO fix differences were larger. Even though no attempt has been made to remove the aircraft bias to the satellite fix within the SAMC data (which would usually act to make the present fix differences larger) relatively large position differences can frequently occur. Although mean differences in the SISO are about a half-degree or 30 n mi (55 km), there is a 10 percent chance of differences being greater than 1 degree or 60 n mi (110 km). If aircraft biases to satellite position could be removed in all the SAMC and SISO data then the positioning differences would probably be larger.

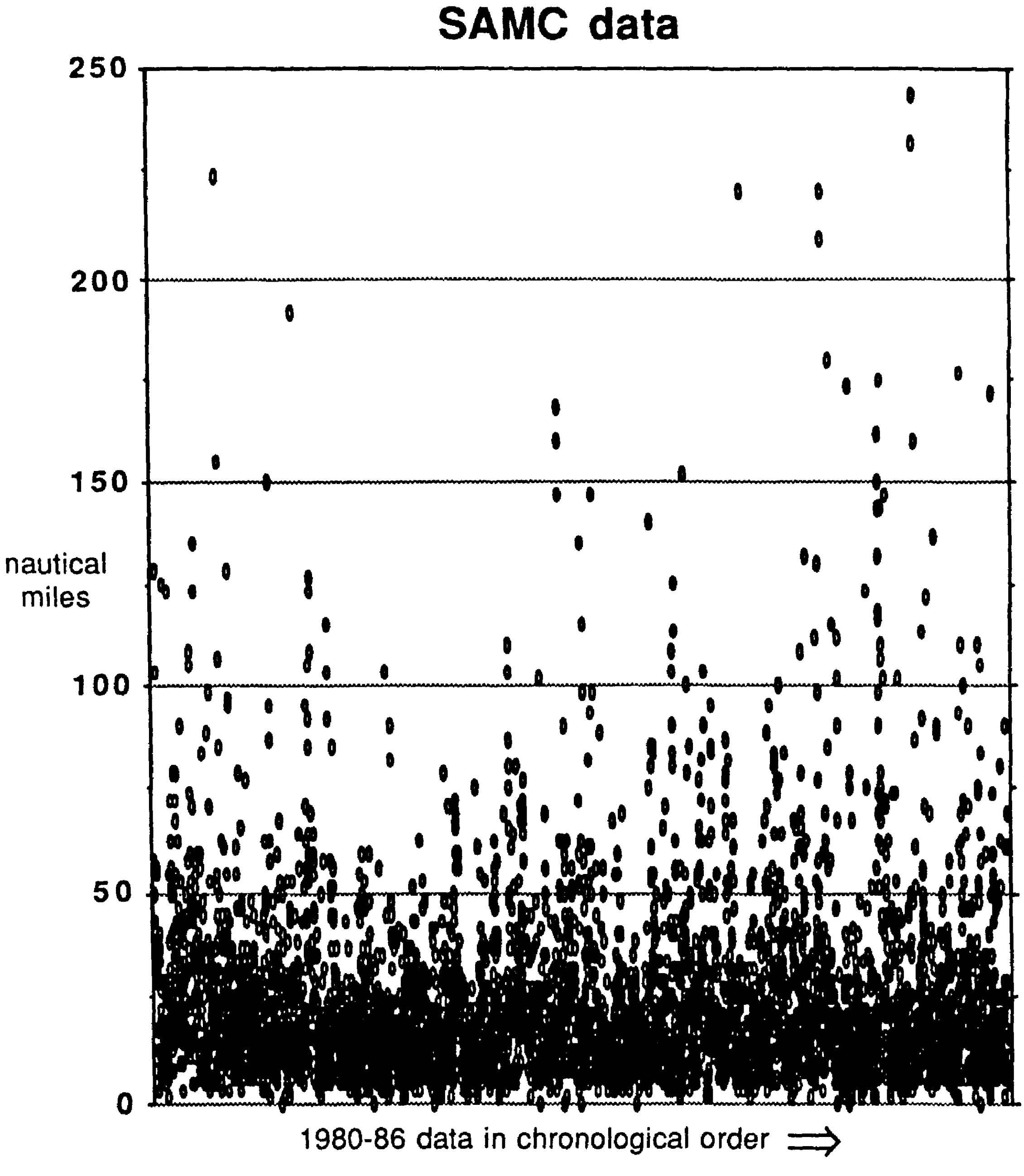


Figure 4.1: Distribution of TC positioning differences as calculated by the Satellite and Aircraft Measurement Comparison (SAMC).

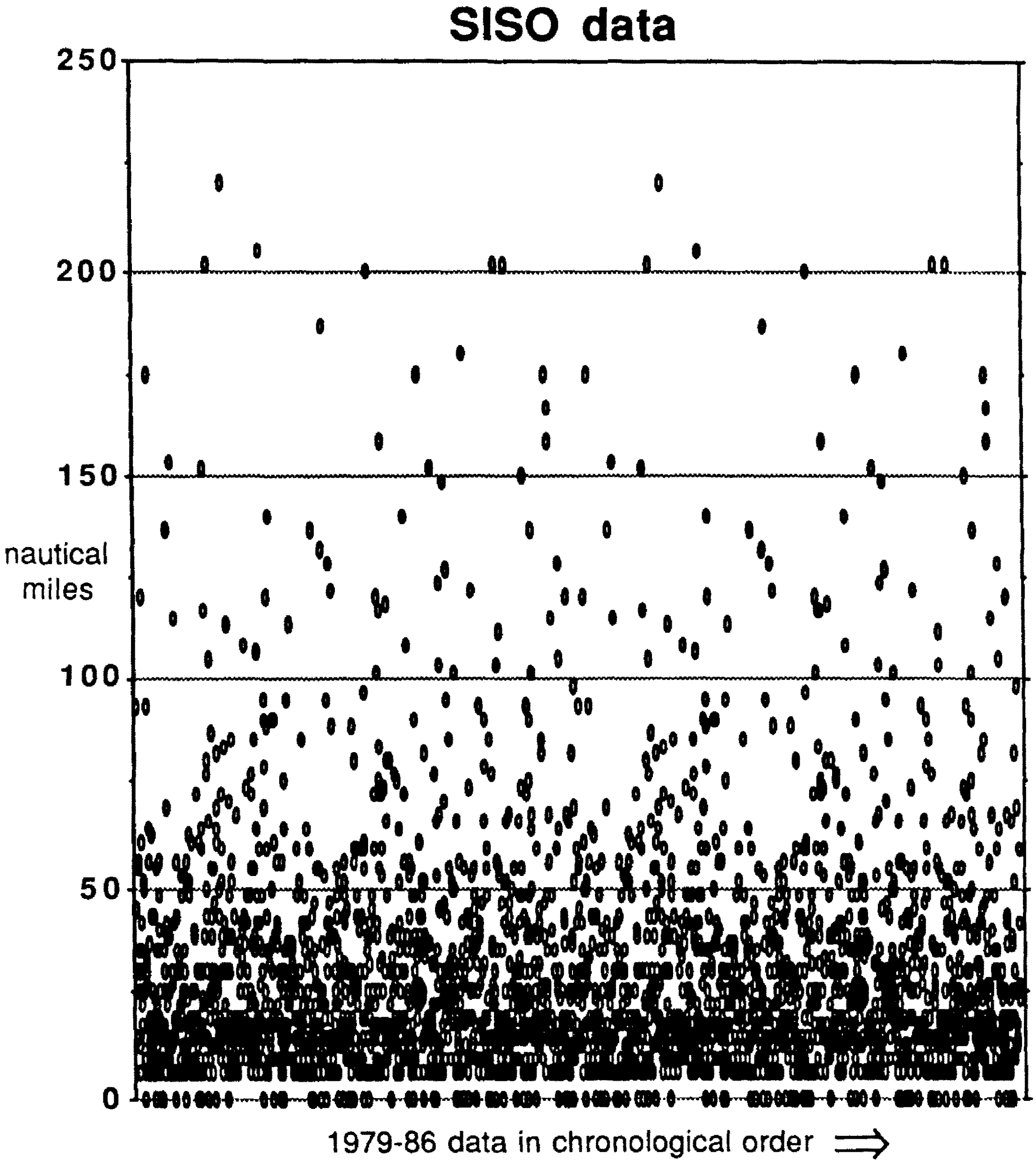


Figure 4.2: Distribution of TC positioning differences as calculated from Simultaneous Independent Satellite Observations (SISO).

Table 4.1: Characteristics of fix positioning differences in the Satellite and Aircraft Measurement (SAMC) and Simultaneous Independent Satellite Observations (SISO) data sets. (1 n mi = 1.85 km).

Statistics	SAMC	SISO
mean	24	30
standard deviation	23	30
10th percentile	6	6
90th percentile	50	62
10th% to 90th% range	44	56
number of cases	4588	2906

all values in nautical miles

4.2 Positioning differences as a function of TC intensity

Position differences are, of course, a function of TC intensity. TC eyes are more frequently present and more easily observable in the more intense TCs and make for easier positioning. Satellite and Aircraft Measurement Comparison (SAMC) positioning differences as a function of storm intensity are presented in Fig. 4.3. Similarly, the Simultaneous Independent Satellite Observations (SISO) information, stratified by TC intensity, is shown in Fig. 4.4. In both figures, mean differences are represented by the thick lines; standard deviations by thin lines. Note the similarity of these two figures. Positioning differences are seen to directly decrease as TC intensity increases. This is a direct function of the increased ability of eye detection in the more intense TCs.

Again, note that aircraft biases to the satellite positioning have not been removed in either data sample—differences are probably smaller than those that would occur if satellite position fixes were completely independent of the aircraft information. It is not

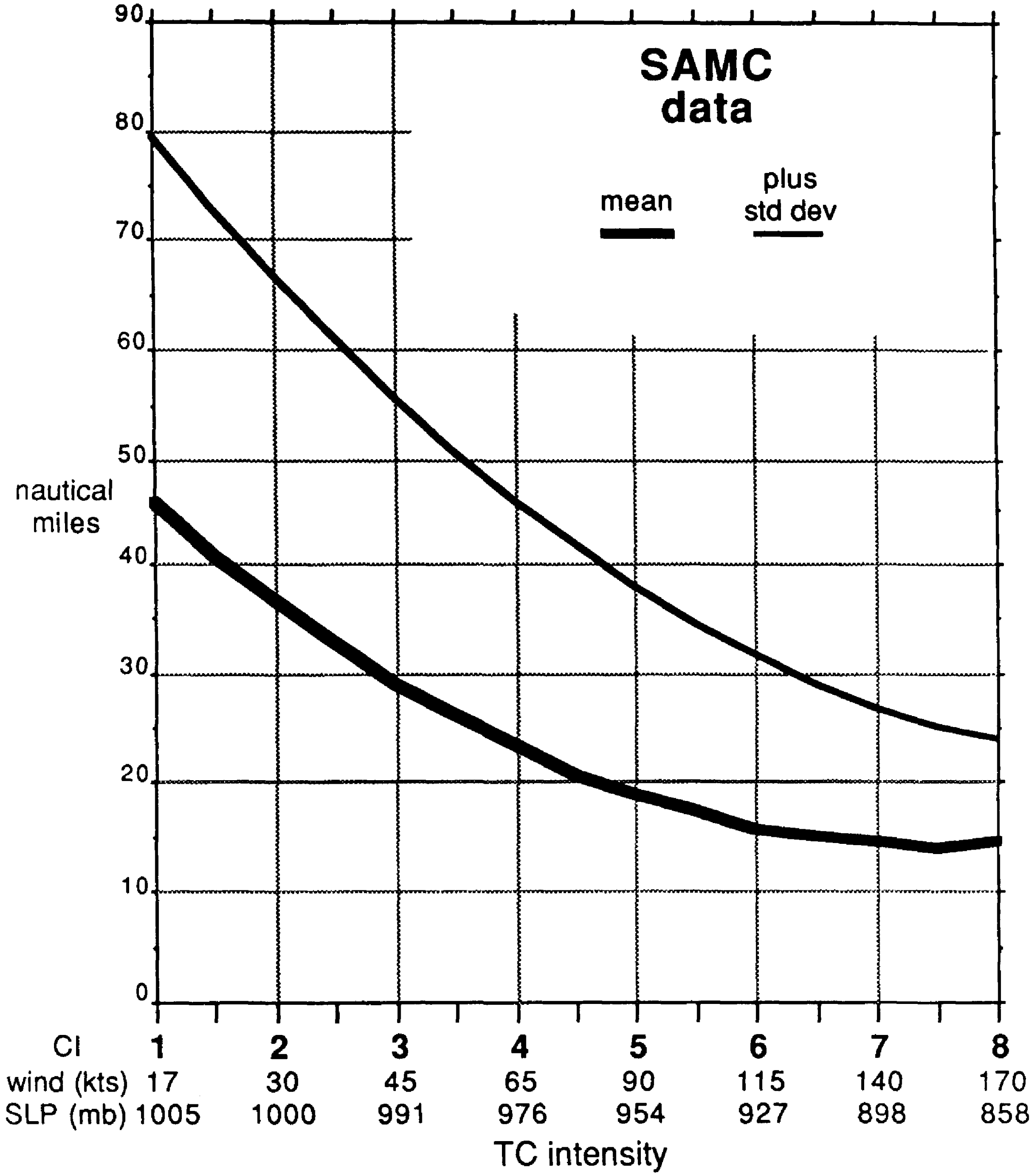


Figure 4.3: Mean plus one standard deviation of Satellite and Aircraft Measurement Comparison (SAMC) TC positioning differences as a function of cyclone intensity.

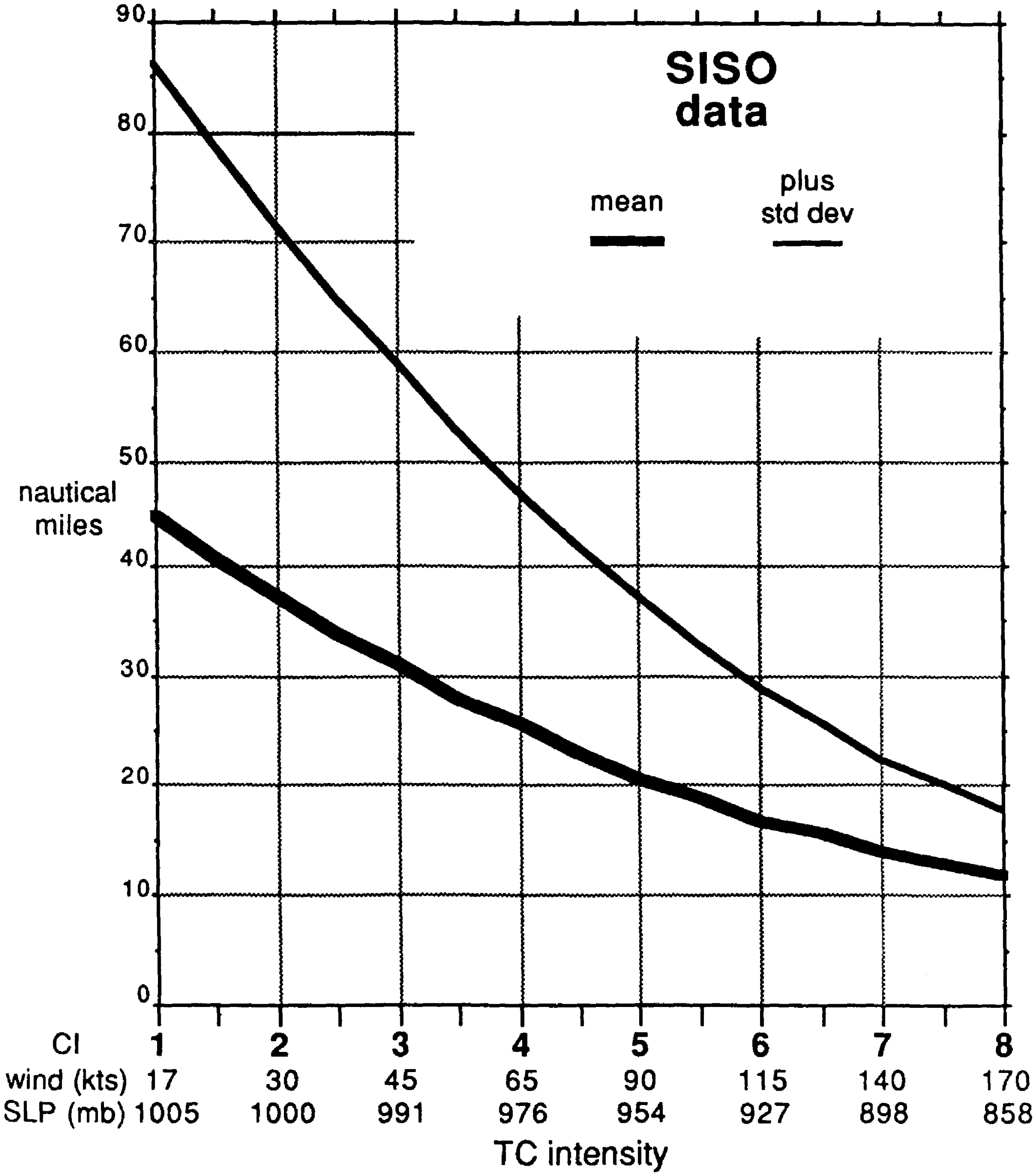


Figure 4.4: Mean plus one standard deviation of Simultaneous Independent Satellite Observation (SISO) derived differences of TC positioning as a function of cyclone intensity.

surprising that differences decrease as the TC becomes more intense and well defined. Notable, however, is that a small percentage of large position differences can still occur even after maximum winds have reached the 65- to 90-knot range. A TC with a maximum wind of about 90 kt (102 mph) includes a 15 percent chance that a satellite fix will differ from the aircraft fix location by 40 n mi (75 km) or greater. Also note that 15 percent of the SISO measurements of 90-knot cyclones differ by nearly 40 n mi (75 km) or greater.

This satellite TC position fix difference is a result of the satellite analyst's frequent inability to precisely determine the TC center and of the satellite gridding (navigation) errors. Although center fix error decreases with cyclone intensity, the gridding of satellite images is more a function of the discernibility of known land features.

One key for estimating TC position from satellite imagery is having a well defined eye. According to a study by Weatherford (1987) the probability that a NW Pacific cyclone will have an eye exceeds 80 percent when the cyclone's central pressure falls below about 950 mb—a CI value of between 5 and 5.5 and maximum sustained wind of 90 knots (see Appendix 3). However, having an eye present does not necessarily mean that the satellite is capable of resolving the eye if it should be obscured by high cloudiness. This is especially the case at night when only infrared (IR) information is available. The type and quality of enhancement used with the IR data may also have an impact on resolving the eye.

Many of these SAMC cases of large position differences are likely a result of the satellite being unable to locate a TC's center which may be quite apparent on an aircraft's radar or directly measured in a routine center fix penetration. Satellite fix location may also be improved through image animation, or looping, of geostationary daytime visual or IR enhanced images. Looping capability has been present in the Atlantic for many years, but not in the NW Pacific (except for Japan). As will be shown later, however, satellite positioning accuracy in the Atlantic has not, in general, been superior to that of the NW Pacific during the period when these different looping capabilities were present. Although looping capability undoubtedly will assist in a number of individual fix determinations, this added capability for NW Pacific analysts probably will not appreciably alter mean positioning uncertainty.

4.3 Day-night comparison of TC positioning differences

Due to night infrared (IR) image resolution of 4-6 km one might expect a decreased center detection capability at night compared with daytime visual imagery where the resolution is 0.5-1.0 km. Although this is found to be true, differences are not as large as expected. Day vs. night positioning differences are depicted in Fig. 4.5 as a function of cyclone intensity. Daytime mean, and one standard deviation differences are represented by the thick and thin black lines, respectively. Night differences are represented by the gray-shade lines. Note the poorer resolution at night, particularly for the weaker intensity cyclones. Results show about 20 percent higher fix position differences (i.e. 15 n mi or 30 km) can be expected to occur at night. One might have expected a larger nighttime positioning degradation. Superior daytime positioning information from visual imagery probably is being carried over to the nighttime hours. An IR only satellite system would likely have shown less nighttime position accuracy than is indicated here.

Figure 4.6 shows similar day vs. night fix differences for the SISO data. Note that day-night differences are again not very large. Mean and 85 percentile daytime SISO position differences are nearly 0.5 and 1.0 degree, respectively.

4.4 Image type comparison of TC positioning differences

Satellite imagery may also be stratified into several subgroupings. First are cases where only visual satellite imagery was used for the fix. Second, are cases where only infrared fix measurements were available. Finally, are situations where both visual and infrared information was available for fix determinations. Interestingly, only small fix differences are observed between these imagery groups. One might expect smaller fix differences when both visual and infrared are available when compared to visual-only or infrared-only cases. Figure 4.7 gives means and standard deviations of positioning difference distributions for each type of image set: visual (VIS), infrared (IR), and both

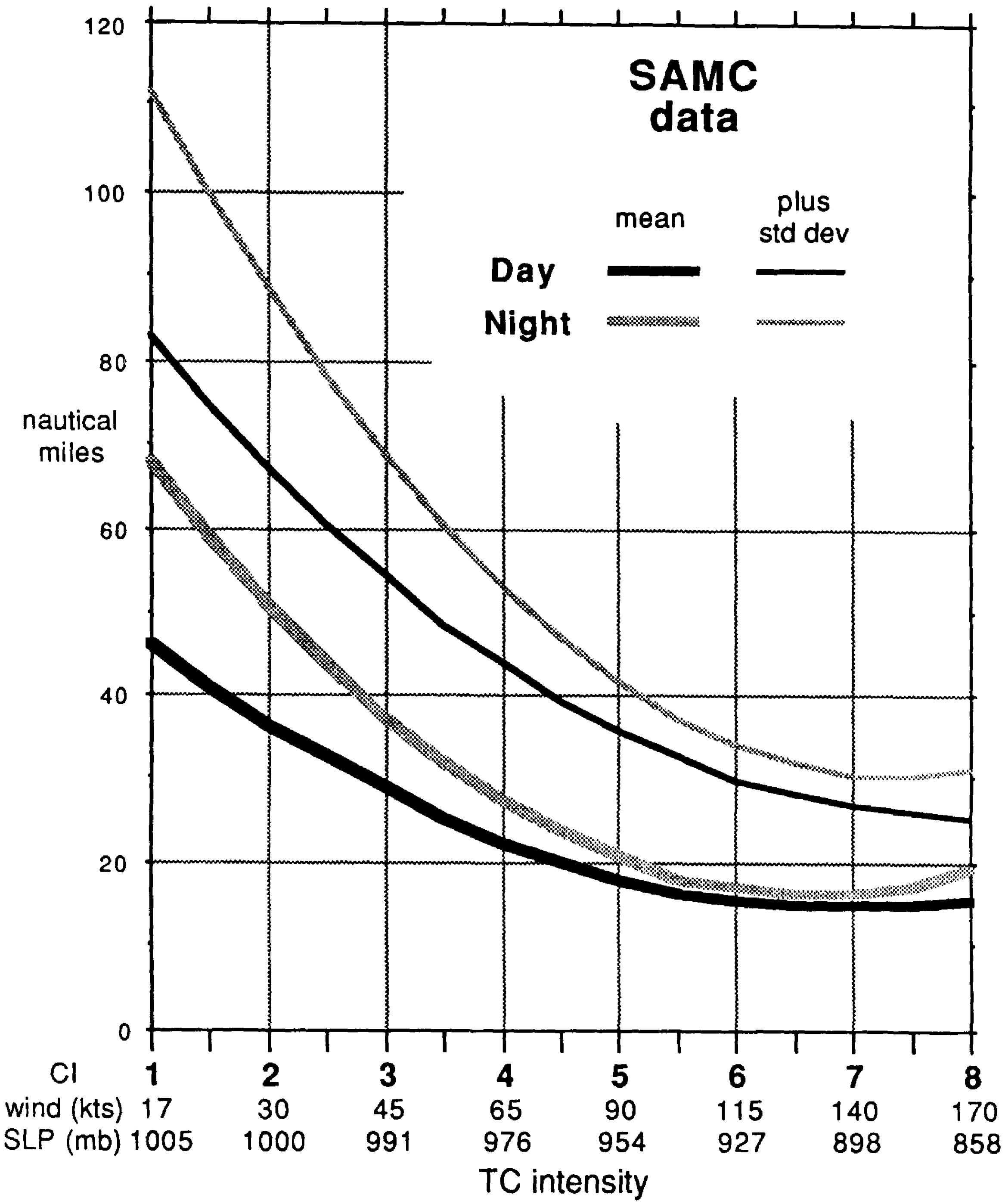


Figure 4.5: Day and night mean and one standard deviation of Satellite and Aircraft Measurement Comparison (SAMC) of TC positioning differences as a function of cyclone intensity.

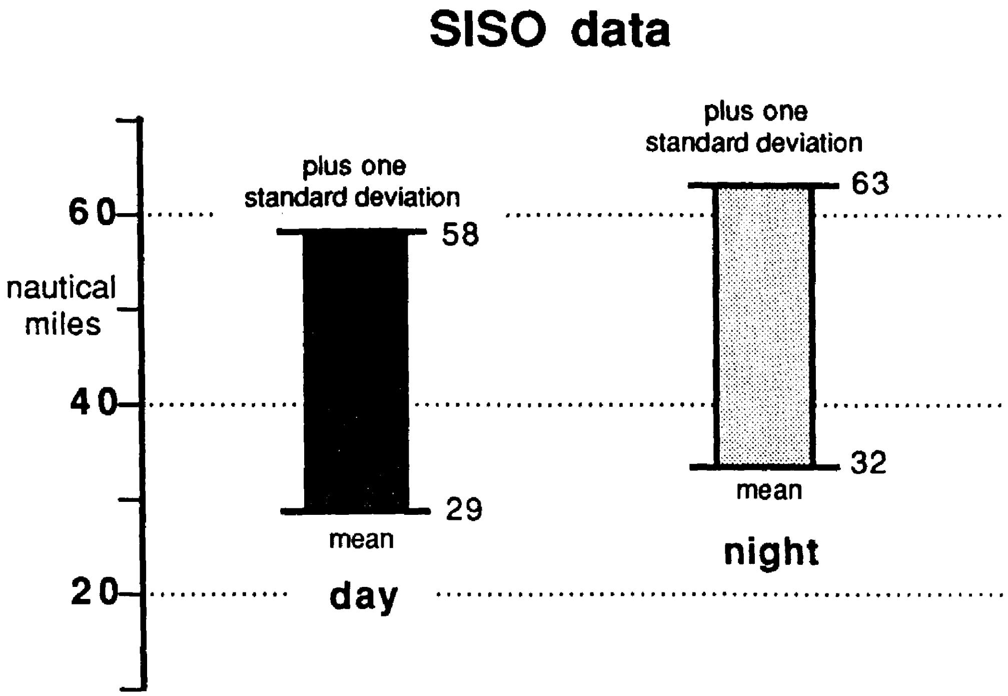


Figure 4.6: Day and night mean and one standard deviation of TC positioning differences as measured by the Simultaneous Independent Satellite Observation (SISO).

VIS and IR. A somewhat larger mean and standard deviation is observed for the IR data. This is further supported from a similar plot, but for SISO data (see Fig. 4.8). One might have expected that a comparison of VIS and IR results would have shown larger differences. Surprisingly, when the operational site has both VIS and IR available, little improvement is indicated over the VIS-only data. These results indicate that the superior resolution of daytime visual imagery does not translate into very superior daytime position fixes. As previously concluded, this may indicate that better resolution visual imagery, used in daytime positioning, is being carried over for an improvement of IR nighttime fixes.

4.5 Comparison of TC positioning differences for specific satellites and satellite types

A further stratification of these position fix distributions was made for individual satellite sensors. This satellite sensor stratification shows the recent chronological trend in satellite technology and in TC position fix uncertainty in the NW Pacific. Figure 4.9 shows mean and standard deviation of satellite minus aircraft position differences from the SAMC data set for each satellite. No significant trends in positioning uncertainty with regard to satellite type or in the time series are observed. Figure 4.10 shows the same analysis but from the SISO data set. The SISO data included far fewer events for the Japanese GMS satellite, since availability of that information was limited to fewer operational sites. The dates the satellite first and last appeared in the SISO data set are also included as an ordered chronological reference. Table 4.2 presents composite statistics for each group of satellites from both data sets. Again, no significant differences are observed among the satellites and no time-series trend is evident.

Results from the SAMC and SISO data sets show consistent patterns. DMSP and NOAA satellite differences appear very similar. GMS fix differences are larger for the SISO difference comparison. This is possibly a result of less sophisticated GMS information at the various NW Pacific operational sites in comparison with polar orbiter analysis data.

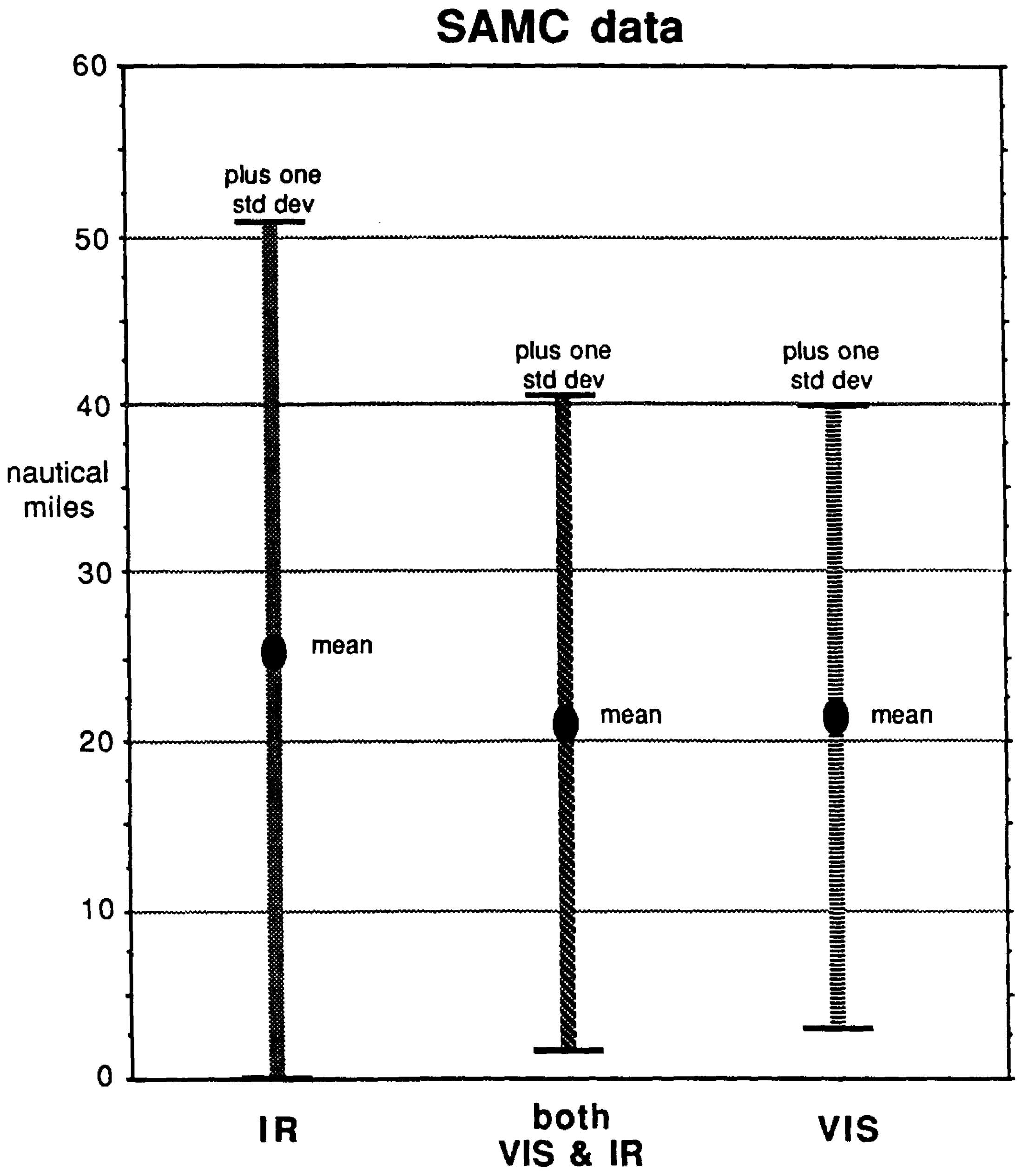


Figure 4.7: Mean and standard deviation of TC positioning differences as derived from Satellite and Aircraft Measurement Comparison (SAMC) for each type of satellite imagery, infrared (IR), visual (VIS), and the IR and VIS combination.

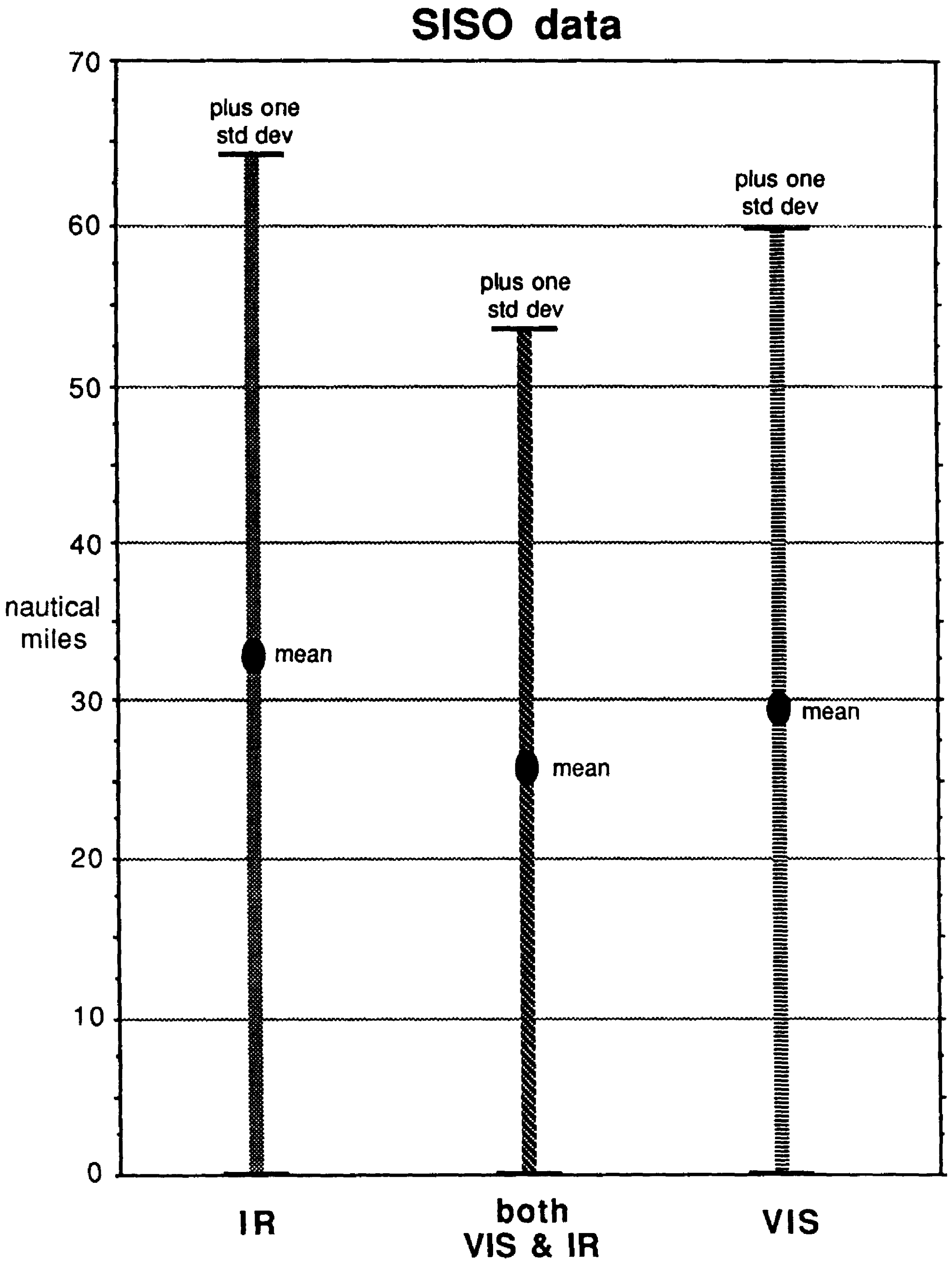


Figure 4.8: Mean and standard deviation of TC positioning differences as derived from Simultaneous Independent Satellite Observations (SISO) for each type of satellite imagery as described in Fig. 4.7.

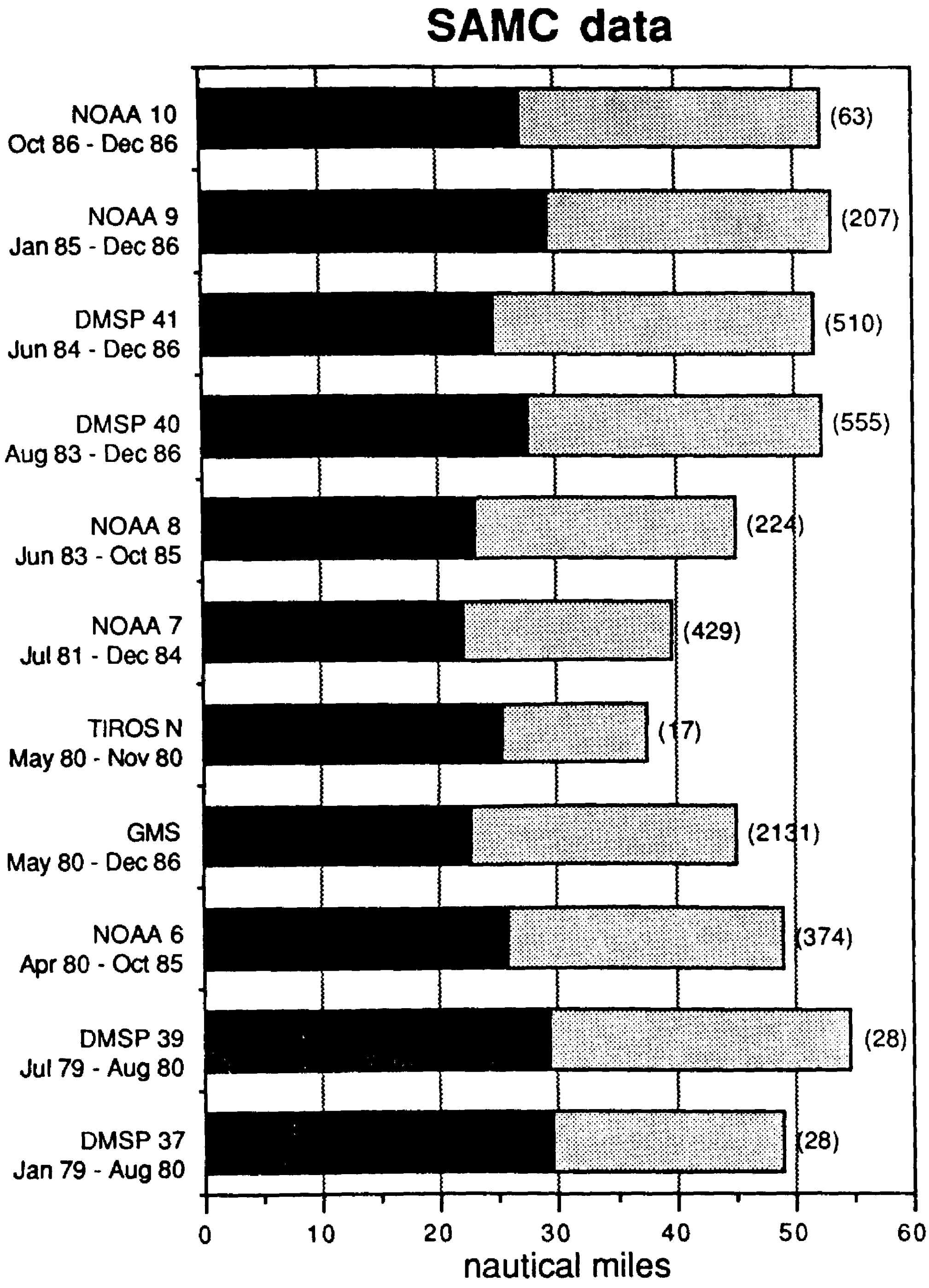


Figure 4.9: Mean (black bar) and one standard deviation (gray bar) of TC positioning differences from Satellite and Aircraft Measurement Comparison (SAMC) for each satellite. Most recent satellites are at the top. The number of observations is in parentheses.

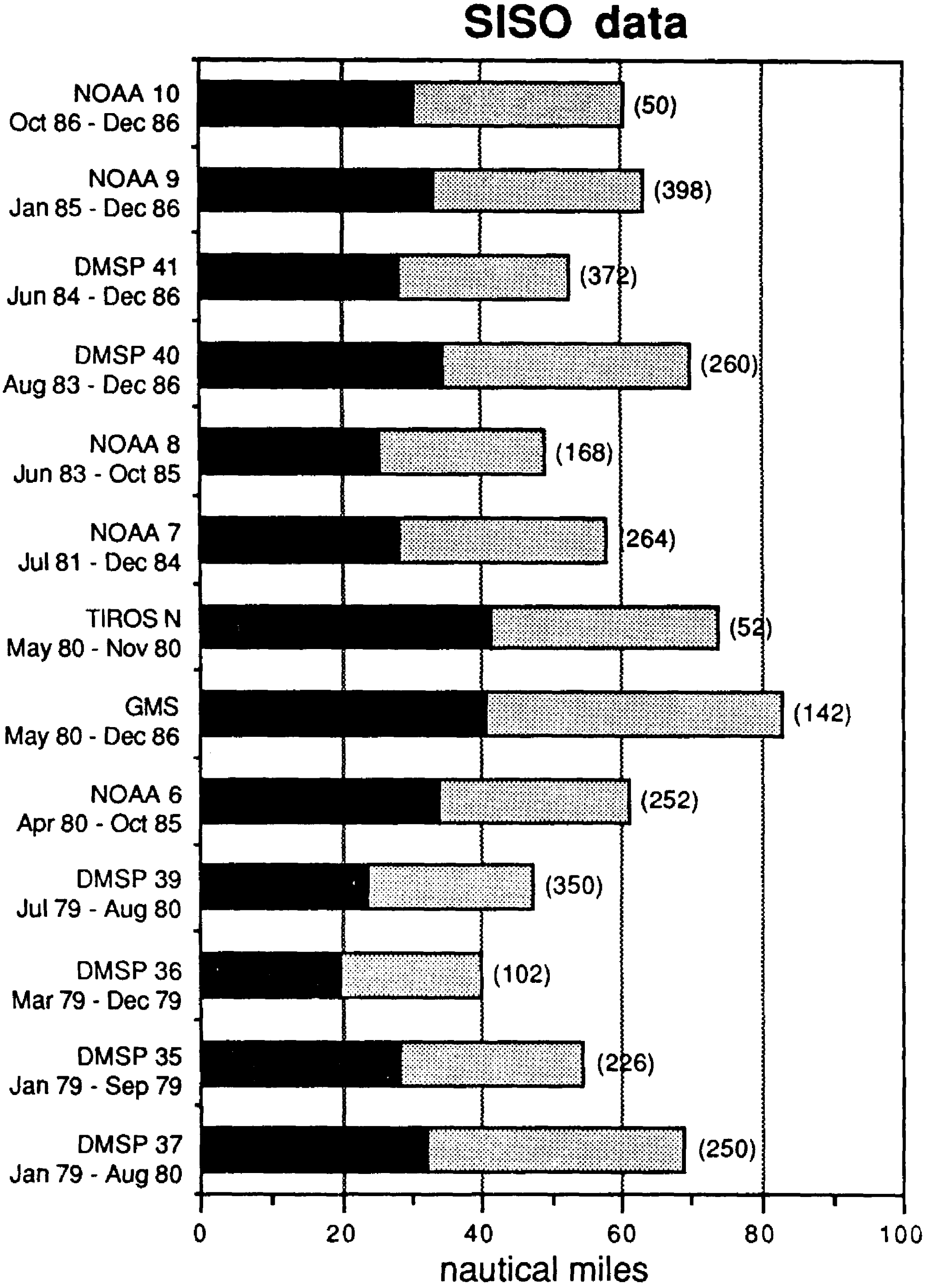


Figure 4.10: Mean (black bar) and one standard deviation (gray bar) of Simultaneous Independent Satellite Observation (SISO) TC fix differences for different satellites. Most recent satellites are at the top. The number of observations is in parentheses.

Table 4.2: Characteristics of positioning differences by satellite class for the Satellite and Aircraft Measurement (SAMC) and Simultaneous Independent Satellite Observations (SISO) data sets.

SAMC data

Statistics	NOAA	DMSP	GMS	TIROS
mean	25	26	23	25
standard deviation	21	26	22	12
mean + 1 std dev	46	52	45	38
range	161	225	232	43
number of cases	1297	1121	2131	17

all values in nautical miles

SISO data

Statistics	NOAA	DMSP	GMS	TIROS
mean	31	28	41	42
standard deviation	28	28	42	32
mean + 1 std dev	59	56	83	74
range	172	174	204	114
number of cases	1132	1560	142	52

all values in nautical miles

One surprise was the failure to find an improvement in fix position accuracy with the more advanced satellites. When satellites were grouped in chronological order no improvement trend was evident. An earlier Atlantic study (Gaby *et al.*, 1980) pointed toward a substantial improvement in satellite fix position uncertainty during the 1970's period. However, the Gaby, *et al.* study ends at the time this study begins. We find no such optimistic trend for improvement in satellite fix potential in the more recent period of the 1980's. Satellite specialists tell us that no new satellite technologies are coming on line in the next few years that should substantially improve the current satellite TC position fix capability.

4.6 Summary

Large positioning differences (> 60 n mi or 1°) can occur between aircraft-satellite fix measurements and between independent satellite fix measurements. Typical mean fix differences are 30 n mi or one-half degree with the highest 10-15 percent of cases being one degree or more. Differences do increase slightly at night and substantially for weaker TCs. No improvement of satellite positioning fix capability has been detected since the late 1970's. It is to be expected that satellite fix inaccuracies will be reduced somewhat as more use and technical development is made of geostationary satellite visual and looping and IR enhanced picture looping techniques. But, this likely increased fix accuracy, in some cases, is not expected to significantly reduce the mean value of the fix inaccuracies here shown.

Chapter 5

SATELLITE MINUS AIRCRAFT TC MOTION DIFFERENCES

Unlike position or intensity which can be directly measured, TC motion requires at least two position fixes. Given the innate problems of accurate single fix positioning and the often-observed irregular small-scale oscillatory and looping motion of TC centers (that may be very accurately positioned by aircraft) the often difficult task of determining a reliable 12-hour TC motion vector can be appreciated. The irregular times of position fixes further complicate this motion determination.

The TC motion vector derived from a smooth and conservative track estimate is most desired in TC track forecasting. The working best track is used to derive the TC motion vector for the operational track forecasts. Typically all fix data from the past 12 to 24 hours are inspected and used in varying qualitative combinations for the most reliable motion vector estimate. Although time and resources did not permit a full study of this motion question, an analysis was made of the systematic motion differences between consecutive satellite derived fixes and consecutive aircraft fixes interpolated to satellite times. Motion vectors were derived from the last two available satellite fixes (typically 2 to 6 hours apart) and the corresponding aircraft time-interpolated track fixes. Typically, the time between aircraft fixes was 4 to 8 hours.

Since average motion information for different speed stratifications will be shown, many of the large individual small period speed oscillations from individual fix oscillations will be reduced in the averaging process. Speed determinations were calculated separately from the time-interpolated (to satellite fix times) consecutive aircraft fixes, then subtracted from the speeds derived from corresponding consecutive satellite fixes.

Figure 5.1 shows a frequency distribution of satellite minus aircraft derived TC speed differences. Note the systematic and larger speeds which occur from the consecutive satellite fixes in comparison with the consecutive aircraft fixes. A tendency for the satellite analyst to move the TC at a faster speed than indicated by the consecutive aircraft fixes is apparent. Although these satellite speed differences would be reduced if longer time period averaging had been taken; they do indicate some potential problems intrinsic to short-period satellite speed determinations.

These satellite minus aircraft speed differences may result from a tendency of the satellite analyst to forward-extrapolate TC motion too rapidly. Irregular and oscillatory TC movements, in general, act to slow-up the longer period TC motion vector.

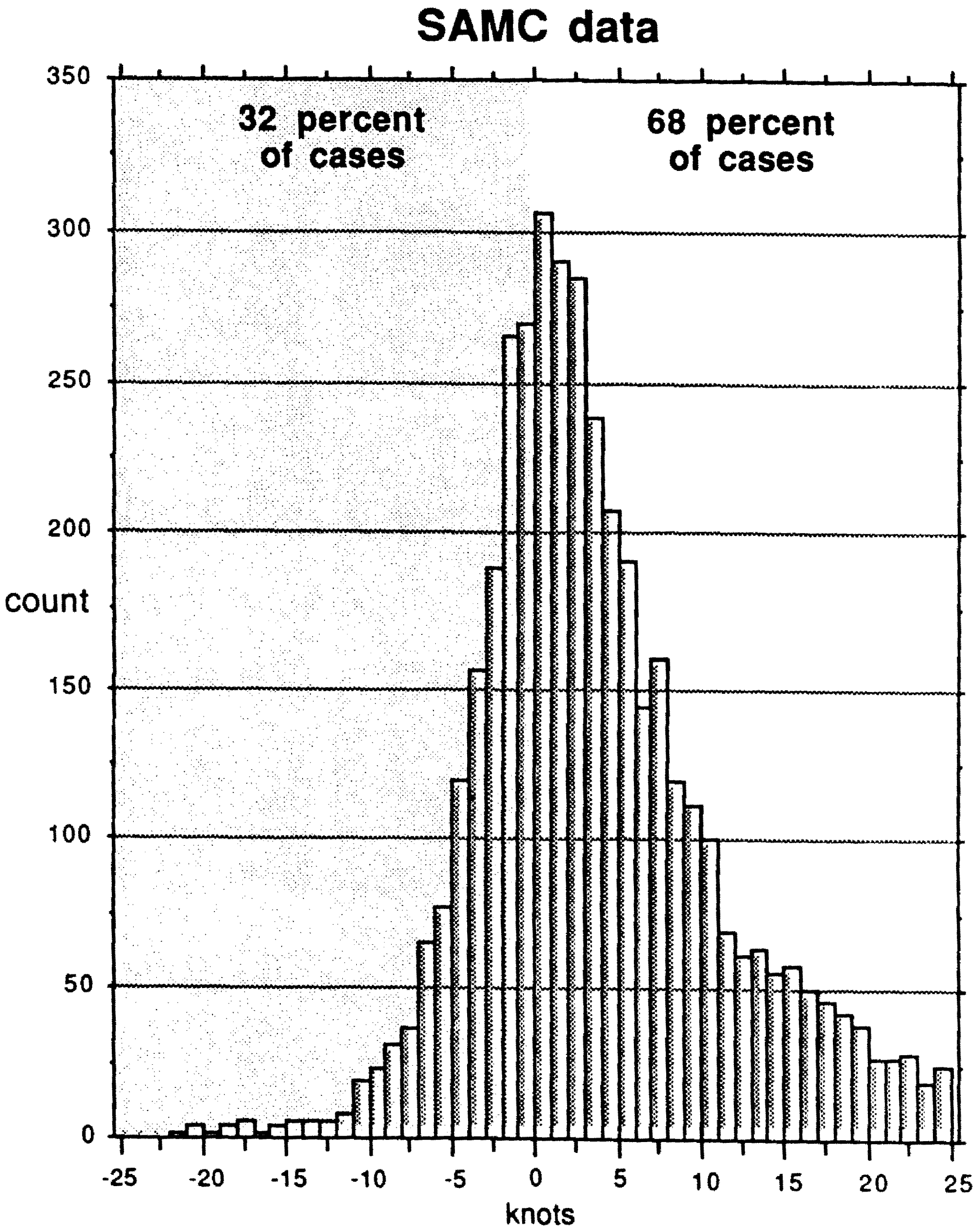


Figure 5.1: Frequency distribution of satellite minus aircraft TC speed differences from two consecutive satellite fixes minus two corresponding time-interpolated aircraft fixes. Information from the SAMC data set.

Chapter 6

TROPICAL CYCLONE INTENSITY ESTIMATE DIFFERENCES

Questions arise as to how accurately TC intensity can be measured from the satellite without the supporting assistance of aircraft reconnaissance. Figure 6.1 shows the distribution of TC intensity differences as measured by the Satellite and Aircraft Measurement Comparison (SAMC). Note that some large (± 20 mb) satellite minus aircraft intensity differences were observed. Intensity differences greater than ± 20 mb are equivalent to about one Dvorak CI number. These intensity differences probably result from the difficulty satellite analysts have in applying a uniform Dvorak intensity scale to all TC classes. Problems arise, particularly with TCs undergoing rapid intensity change and for filling TCs.

Figure 6.2 is a similar scattergram but from the Simultaneous Independent Satellite Observations (SISO) of TC intensity. Differences are depicted as absolute differences with no regard to sign of the differences. Although satellite analysts who independently estimate intensity, of the same TC at the same time, can occasionally have rather large differences in their intensity estimates, generally their estimates are very consistent.

Table 6.1 shows the mean, standard deviation, 10th percentile, 90th percentile, and 10th to 90th percentile range of TC intensity estimate differences from both SAMC and SISO data. SISO intensity estimate differences are significantly smaller than those of the SAMC intensity differences. These results are opposite to the SAMC and SISO position fix comparison.

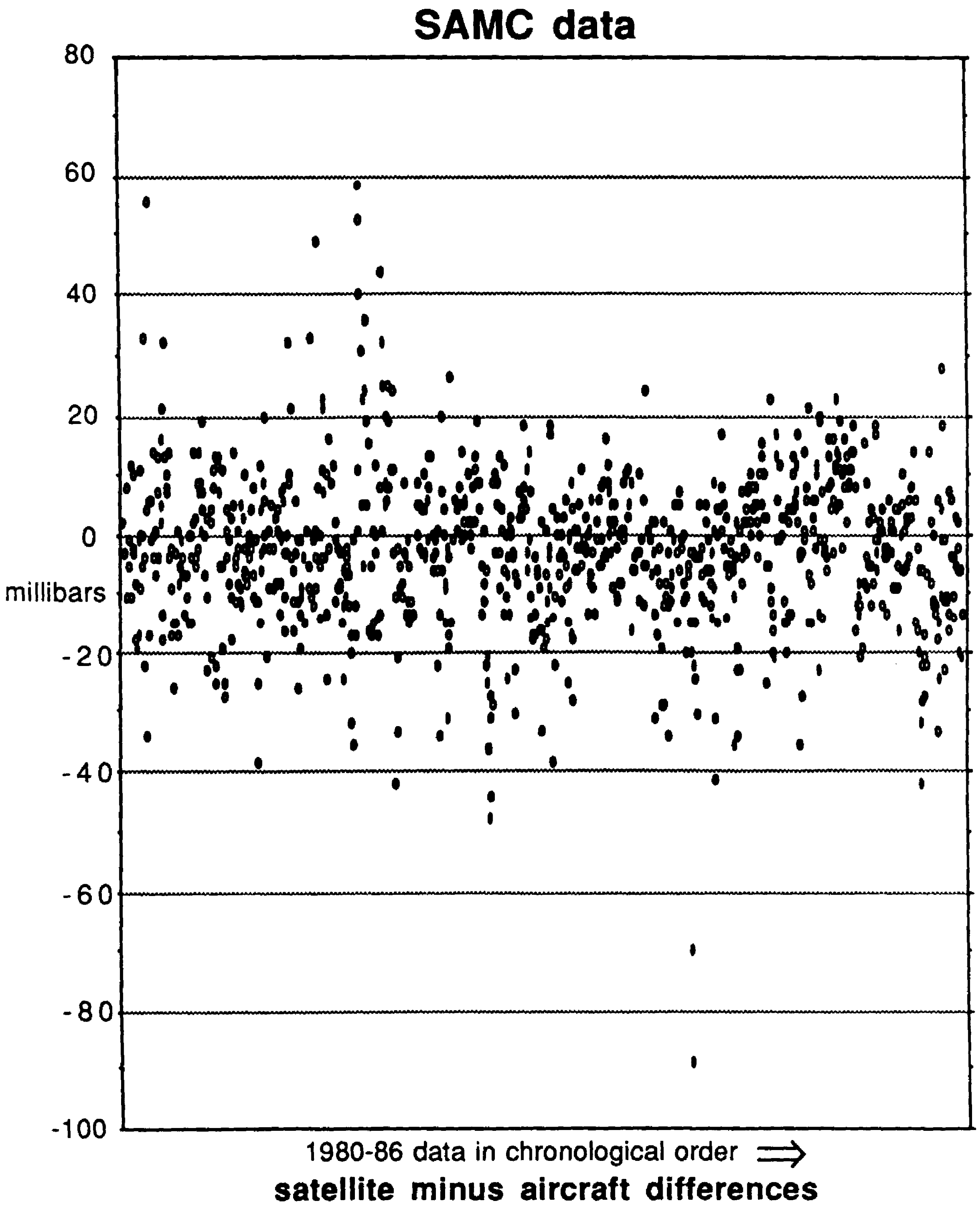


Figure 6.1: Distribution of differences of satellite estimated minimum sea-level pressure (MSLP) minus aircraft measured MSLP. Data from the SAMC data set.

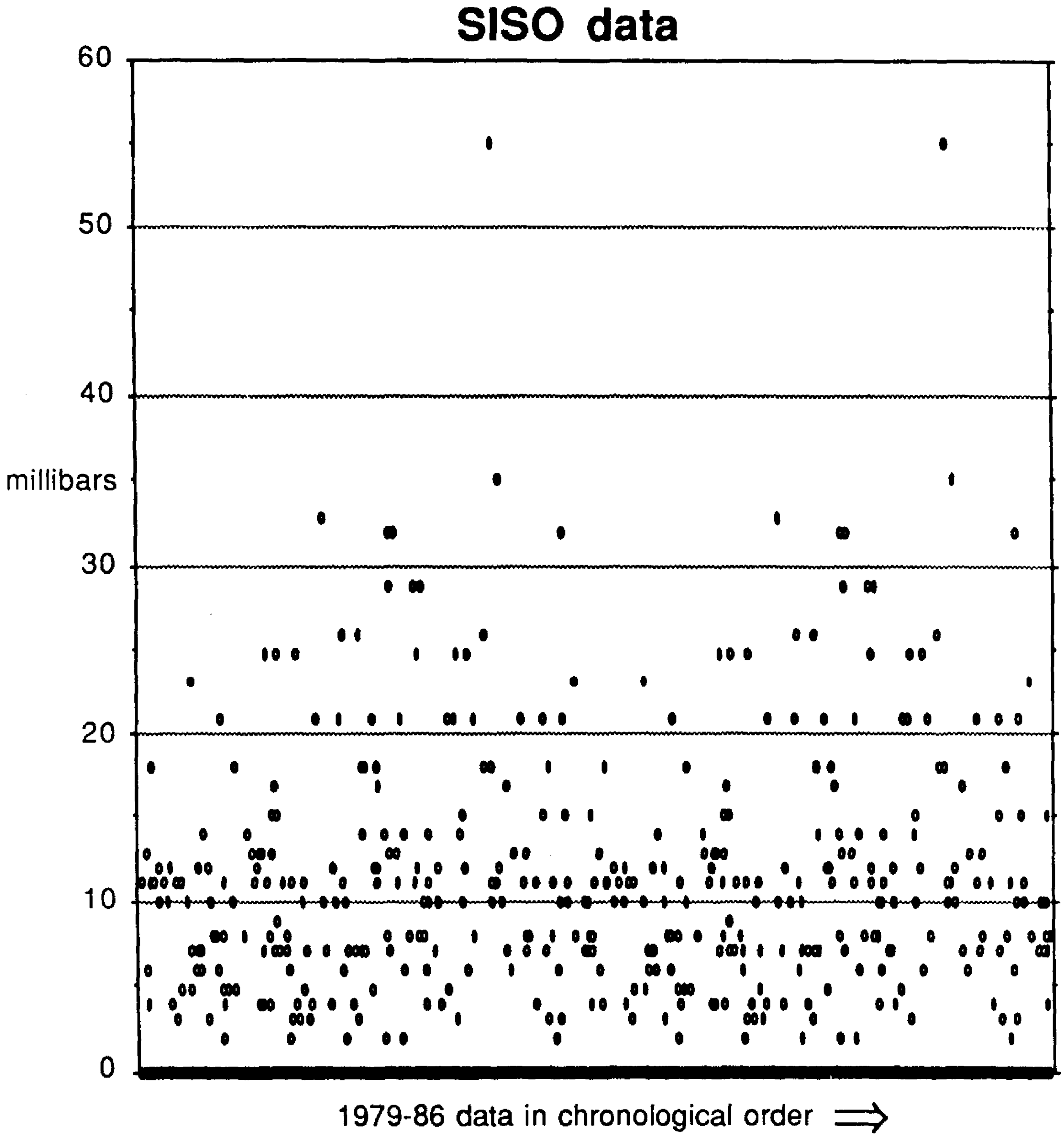


Figure 6.2: Simultaneous Independent Satellite Observations (SISO) of absolute TC Minimum Sea-Level Pressure intensity differences. Data clustering causes the thick black line at the 0 difference value.

Table 6.1: Characteristics of TC intensity differences, in terms of central pressure, of the satellite minus aircraft measurements in the SAMC data set and of the Simultaneous Independent Satellite Observations (SISO) data set.

Statistics	SAMC	SISO
mean	10	3
standard deviation	9	6
10th percentile	1	0
90th percentile	21	11
10th% to 90th% range	20	11
number of cases	1013	1640

all values in millibars

6.1 Discussion of differences in SAMC vs. SISO intensity estimation

The closeness of the SISO intensity estimates may be the result of the satellite analysts making their intensity estimates in distinct and limited Dvorak number categories (Dvorak, 1984). Satellite analysts must choose selective intensity categories and follow prescribed patterns for a change of CI categories. Nevertheless, SISO intensity estimate differences were significantly smaller than the SAMC intensity estimate differences. This implies that there is much greater consistency, but not necessarily accuracy, in the SISO measurements compared with the SAMC data.

The SISO data also were analyzed to determine if cases when reconnaissance aircraft were flown in the 12-hour period prior to the intensity determination had reduced SISO intensity estimate differences over cases when aircraft were not flown in the previous 12-hour period. Lesser positioning differences had been noted when aircraft fixes were available from a similar analysis in Chapter 4.

Figure 6.3 shows that such an aircraft improvement to SISO intensity estimates did not take place. In fact, the reverse occurred. Those SISO intensity estimate differences having 12-hr prior aircraft information were larger than those SISO intensity estimates without aircraft. Thus, having aircraft within 12 hours of the satellite intensity estimates increased SISO intensity estimate differences.

These results may appear surprising initially. They may be a consequence of the confusion which may occur in the satellite analysts' minds when they are confronted with conflicting satellite vs. aircraft TC intensity information. When satellite analysts have only their satellite data to consult, they will more often follow prescribed Dvorak satellite techniques and show more uniformity in their intensity estimates. The Dvorak intensity estimate scheme attempts to follow a more standardized TC intensity life cycle curve. Less scatter might then be expected to occur in the SISO TC intensity estimate differences without prior aircraft data than the scatter in SISO intensity estimate differences when aircraft data were available. Aircraft data upset the pure satellite interpretation.

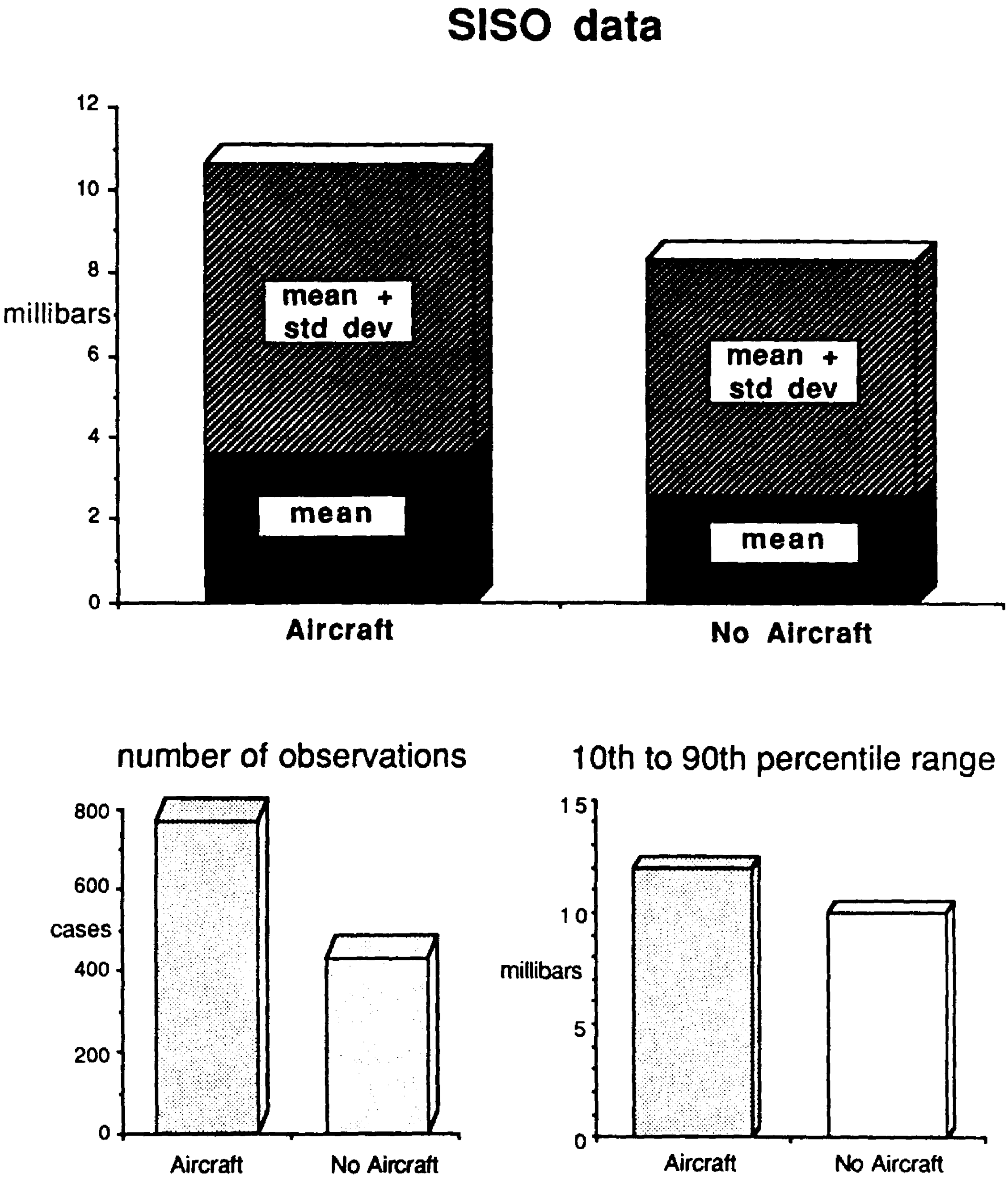


Figure 6.3: Comparison of Simultaneous Independent Satellite Observation (SISO) TC intensity differences between cases when aircraft measurements were and were not available in the 12 hours prior to the SISO measurement. Mean and one standard deviation values shown (top) along with the number of cases studied (lower left) and the range in values from the 10th to 90th percentiles (lower right).

Future multiple satellite TC intensity estimates in the NW Pacific after the discontinuance of aircraft reconnaissance should thus show less scatter than when both satellite and aircraft measured intensity information was available. This projected reduction in scatter for TC intensity estimate differences should not be interpreted as an improvement of satellite intensity estimates. Intensity estimates likely will not be improved and probably will be less accurate than when there was a mix of satellite and aircraft that allowed a more direct observation of satellite intensity.

Figure 6.4 shows a comparison of mean and mean plus one standard deviation of SAMC and SISO intensity estimate differences when aircraft data was available in the previous 12-hour period. Note how the simultaneous satellite observers tended to believe their satellite intensity estimates rather than abandoning their estimates more in favor of the aircraft intensity estimates. The shaded area in this figure indicates the intensity bias.

6.2 Satellite minus aircraft TC intensity estimate differences as a function of storm intensity

Are the systematic satellite minus aircraft intensity differences associated with TC intensity? Figure 6.5 shows such differences as a function of TC intensity. Note that for the intense TC there is a tendency for the satellite to overestimate the cyclone's intensity by 10-15 mb. This may be a result of the conservatism of the Dvorak scheme. For instance, it is prescribed that the forecaster wait at least 12 hours to confirm a filling intensity change. This would produce an overestimate of intensity. Satellite analysts may thus be somewhat behind in their estimates of TC filling and sudden intensity change.

Figure 6.6 is a plot of TC intensity differences as determined from the Simultaneous Independent Satellite Observations (SISO) data. Results indicate a surprisingly good agreement of intensity estimation between independent satellite observers. Eighty-five percent of the satellite analysts agree with each other's TC satellite intensity estimate to within 10 mb. Remarkably consistency is present. Average differences were only 3 mb. This substantiates the strong internal consistency within the TC satellite community in applying the Dvorak rules to intensity estimates. When aircraft data were available

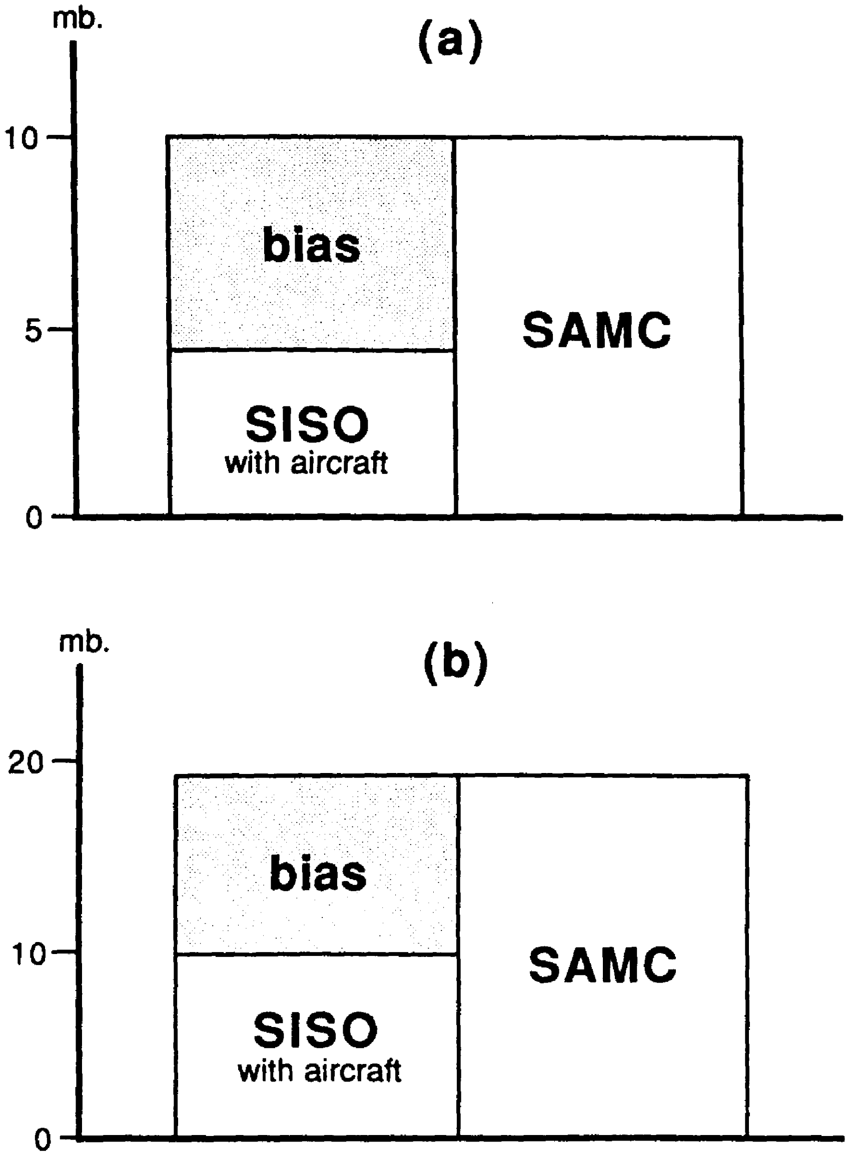


Figure 6.4: Comparison of mean (a) and mean plus one standard deviation (b) of SAMC and SISO that had prior aircraft intensity estimate differences. Shaded area shows the degree of SISO intensity bias.

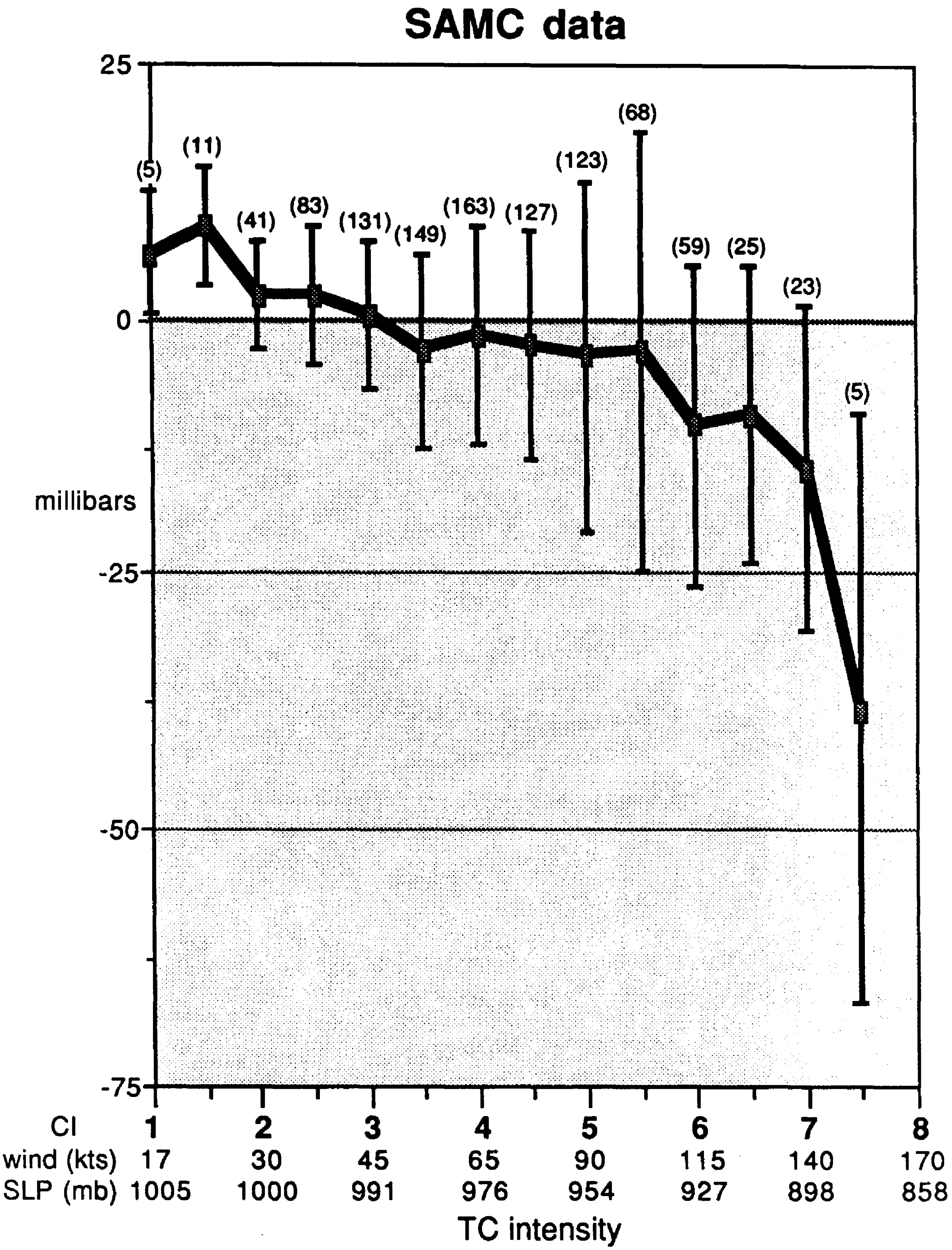


Figure 6.5: Satellite minus aircraft TC intensity differences as a function of cyclone intensity. Mean and one standard deviation values are indicated by the vertical lines. Parentheses indicate the number of cases.

for intensity verification, however, this internal consistency between different satellite vs. satellite intensity estimates is weakened.

6.3 Day-night comparison of TC intensity estimate

As with position fix estimates, it is to be expected that satellite intensity estimates would be more difficult at night than during the day. Figure 6.7 shows day vs. night satellite minus aircraft estimates of TC intensity from the SAMC data. Surprisingly, no differences were noted in the standard deviations of TC intensity between day and night. This lack of day-night differences in intensity estimation may again be a result of the carryover of better satellite daytime intensity estimates to the nighttime along with the conservative nature of the Dvorak intensity estimation technique.

6.4 TC intensity estimates by satellite imagery type

Does satellite imagery type play a role in intensity estimate accuracy? Figure 6.8 shows the distributions of intensity estimate differences from the SAMC data by the three basic imagery (VIS, IR, VIS+IR) classes. Note that a definitive pattern is not present. Having both visual and IR satellite data did not improve over IR or visual information alone as far as the closeness of satellite intensity estimates to aircraft intensity measurement is concerned.

6.5 Comparison of TC intensity estimate differences for specific satellite types

Tropical cyclone intensity was also studied by satellite type. Do the more recent satellites give better observations of TC intensity? Figure 6.9 shows absolute values and standard deviations of TC intensity estimate differences from satellite vs. aircraft estimates from the SAMC data analysis. No obvious chronological trend or individual satellite trend is apparent. Note the small sample size in two outlying cases. Mean differences are about 10 mb with highest 15 percent of observations showing intensity differences between satellite and aircraft measurements of about 20 mb.

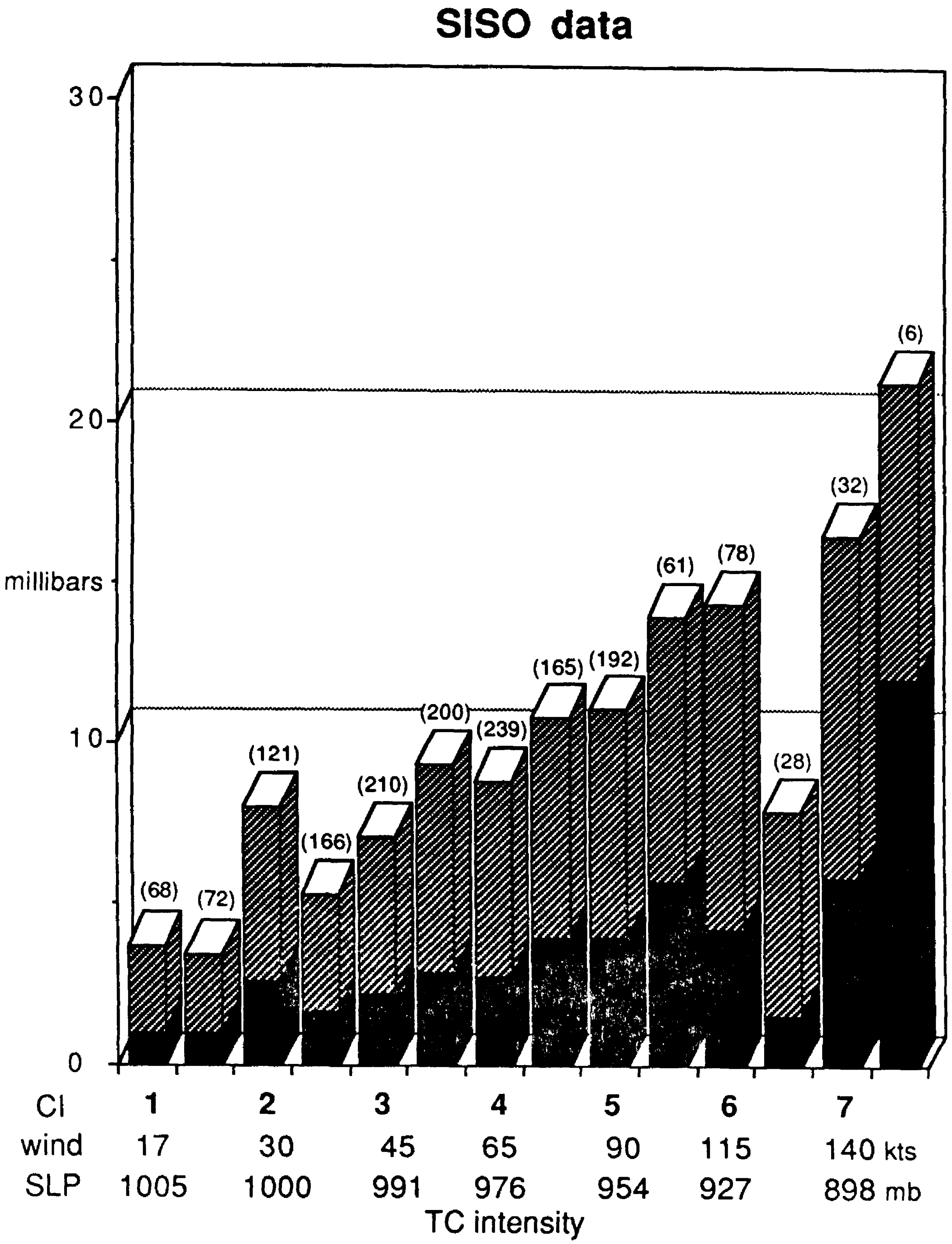


Figure 6.6: Intensity differences as a function of cyclone intensity as measured by Simultaneous Independent Satellite Observations (SISO) observations. Mean (black) and one standard deviation (stippled shading) are indicated. Parentheses show number of cases.

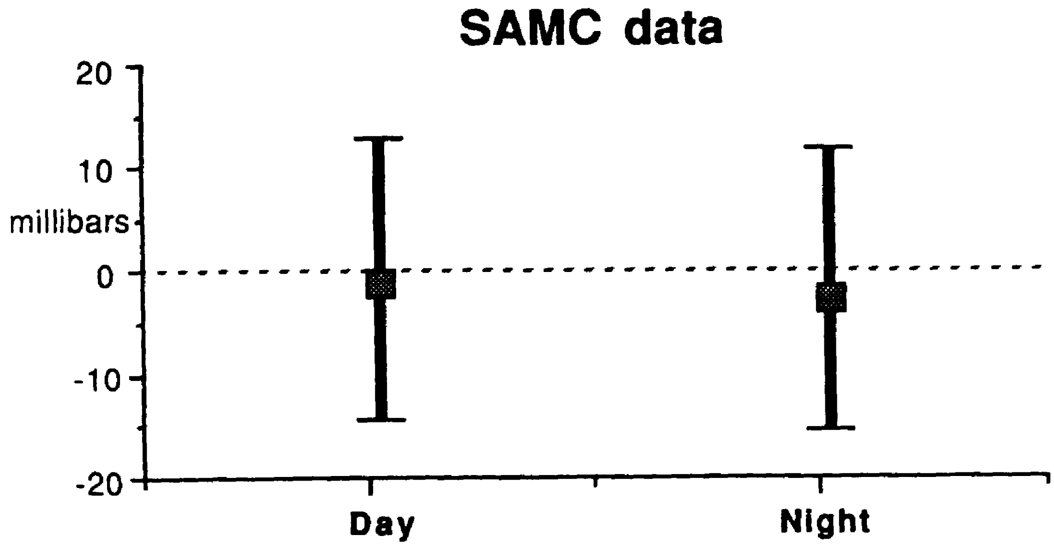


Figure 6.7: Satellite minus aircraft TC intensity differences by day and by night as measured by SAMC data. Mean and one standard deviation portrayed by the vertical lines.

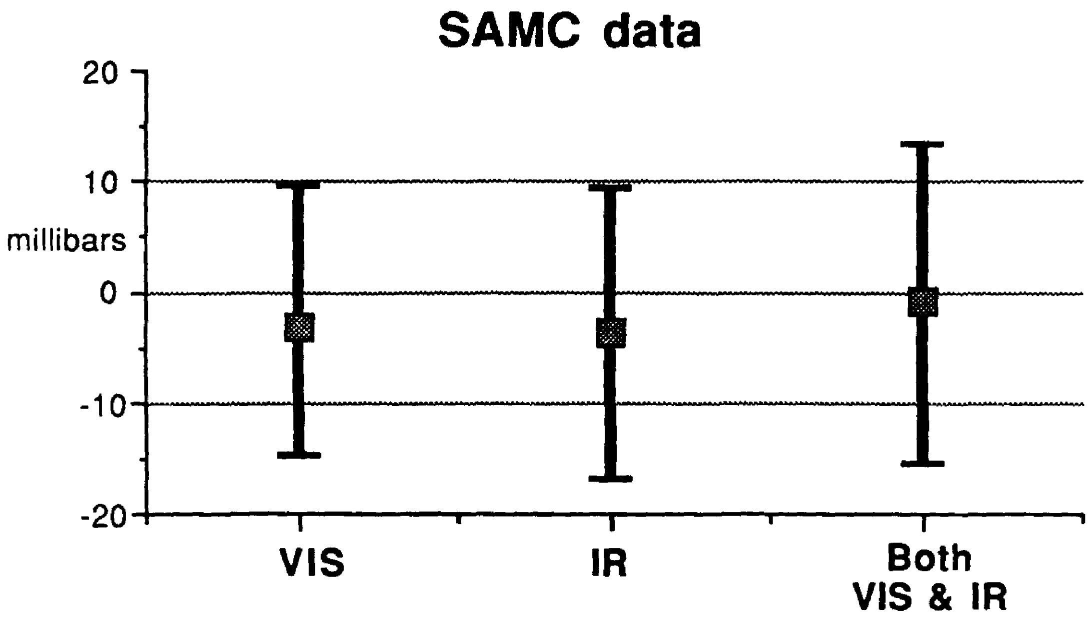


Figure 6.8: Satellite minus aircraft TC intensity differences as a function of satellite imagery type as determined by SAMC data. Mean and standard deviation portrayed by vertical lines. Infrared (IR) and visual (VIS) imagery and both VIS and IR data.

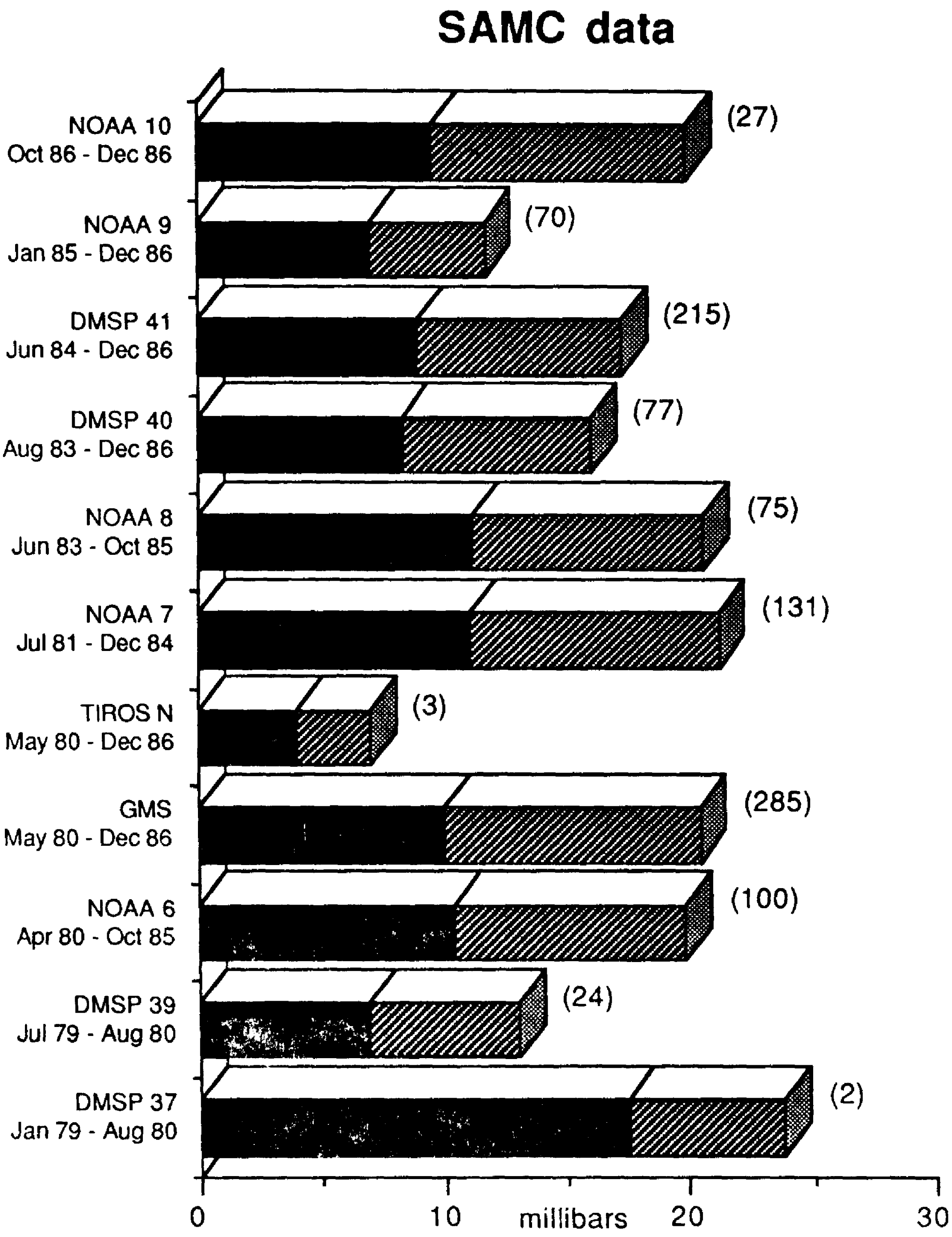


Figure 6.9: Satellite comparison of TC intensity differences between satellite and aircraft (from SAMC data set). Absolute differences of mean (black bar) and standard deviation (gray bar) of TC minimum sea-level pressure are shown. Satellites are arranged in chronological order with the most recent at top. The number of observations is in parentheses. TIROS N and DMSP 37 have unrepresentative low sample sizes.

Figure 6.10 shows similar information for the SISO data set. Again no chronological or satellite type differences were found. But, intensity estimate differences for the satellite vs. satellite estimates are much smaller than from the SAMC intensity differences.

Table 6.2 shows statistical information on both the SAMC and SISO data sets by satellite type. Note how similar the intensity estimate differences are between the different satellite systems. Also, note how consistently smaller are the satellite vs. satellite measurements of TC intensity are as compared to the intensity differences derived from the satellite vs. aircraft comparisons.

6.6 Discussion

One must be very careful in interpreting the ability of the satellite to measure TC intensity when the only source for comparison and verification is the satellite data itself. Direct aircraft intensity measurements must be factored into any realistic determination of how well the current satellite systems are able to measure TC intensity over the open ocean.

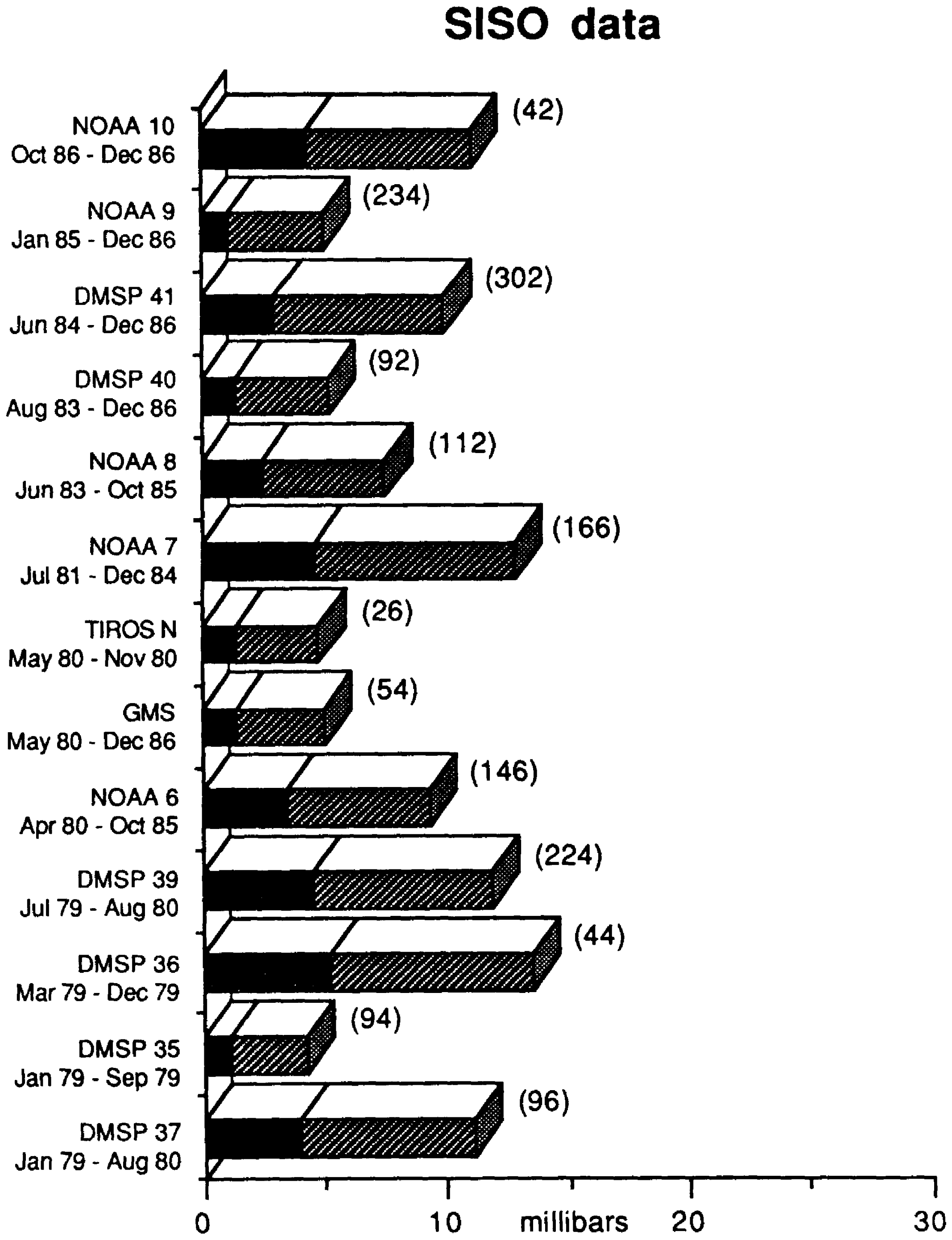


Figure 6.10: Satellite comparison of TC intensity differences between Simultaneous Independent Satellite Observations (SISO). Absolute differences of mean (black bar) and standard deviation (gray bar) of minimum sea-level pressure are shown for each satellite. Satellites are arranged in chronological order with the most recent at top. The number of observations is in parentheses.

Table 6.2: Characteristics of TC intensity differences by satellite class for the Satellite and Aircraft Measurement (SAMC) and Simultaneous Independent Satellite Observations (SISO) data sets.

SAMC data

Statistics	NOAA	DMSP	GMS
mean	10	9	10
standard deviation	9	8	10
mean + 1 std dev	19	17	21
range	44	59	89
number of cases	403	318	285

all values in millibars

SISO data

Statistics	NOAA	DMSP	GMS	TIROS
mean	3	3	1	1
standard deviation	6	7	4	3
mean + 1 std dev	9	10	5	5
range	27	37	15	11
number of cases	700	852	54	26

all values in millibars

Chapter 7

DAMAGE THREAT UNCERTAINTY (DTU)

An attempt to combine TC satellite positioning uncertainty with TC intensity and illustrate some measure of satellite-derived damage uncertainty was deemed useful. This parameter was based on the combination of satellite positioning inaccuracies and potential damage resulting from high winds and surge action. As TC destruction from wind and storm surge is more a function of the cyclone's maximum wind speed squared (V_{max}^2) than the maximum wind itself, we have developed a formula that defines the Damage Threat Uncertainty as (D x V_{max}^2)

where D = position uncertainty of the satellite fix and

V_{max}^2 = cyclone maximum wind speed squared.

Fix positioning uncertainty or D error typically goes down with TC intensity while V_{max}^2 goes sharply up with intensity. Figure 7.1 shows that even though satellite fix position uncertainty goes down with TC intensity, the Damage Threat Uncertainty (DTU), as here defined, rises with TC intensity. Small errors in the positioning of intense cyclones can thus have major influences on increasing the DTU. Small position inaccuracies of intense cyclones are very detrimental to the accurate pin-pointing of the small inner-core swath of major TC destruction.

If aircraft reconnaissance is not available, then vulnerable coastlines in need of very accurate TC fix information should try to have weather radar data available. But the typical area of radar coverage (150-200 n mi) is usually not large enough to give sufficient forecast warning time for preparation–evacuation especially for moderate to fast moving TCs and in those conditions where at least 12 hours or more of daylight preparation-evacuation time is required. By the time the TC eye is observed by coastal radar, outer

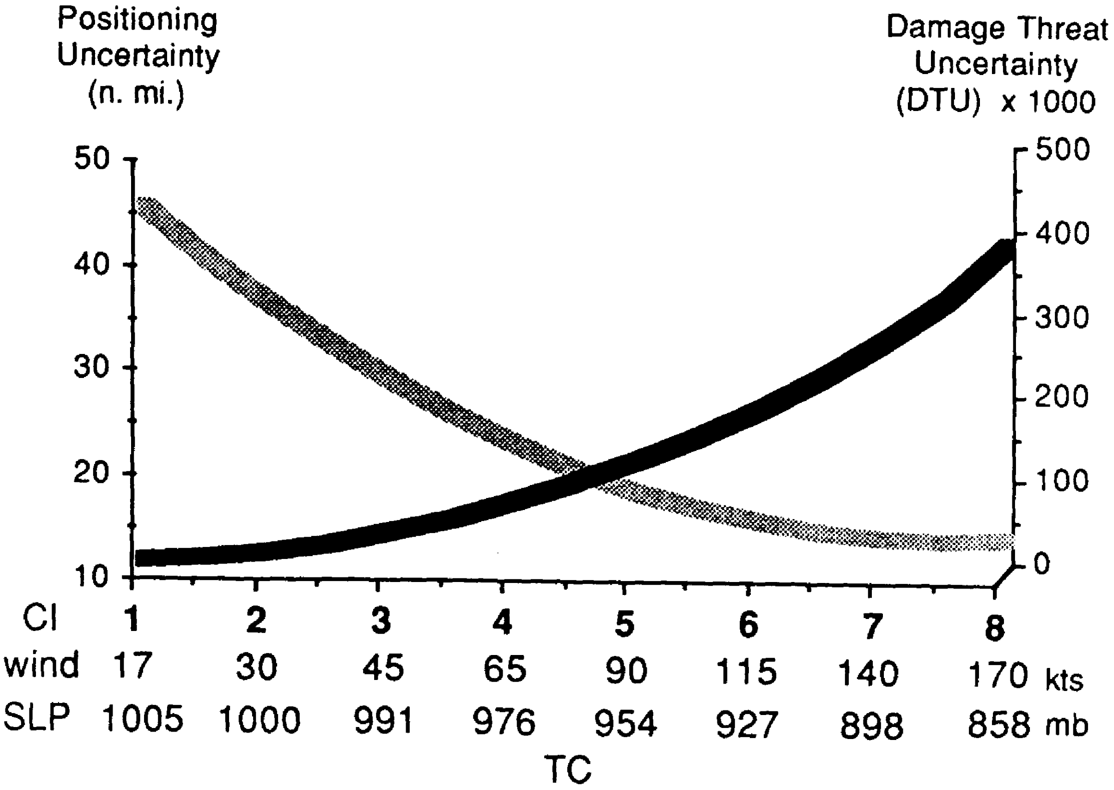


Figure 7.1: Illustration of how Damage Threat Uncertainty (DTU) rises with TC intensity even though position uncertainty decreases. Mean positioning uncertainty is given on left scale (gray line). DTU (right scale, black line) is calculated as the square of the cyclone's maximum wind speed (V_{max}^2) times the positioning uncertainty (D).

TC wind and rain have frequently commenced making evacuation and preparedness much more difficult or impossible.

Chapter 8

THE INFLUENCE OF AIRCRAFT RECONNAISSANCE ON TC TRACK FORECAST ACCURACY

Initial TC position and TC motion vector information are known to be crucial components to accurate short-range prediction. Initial position and motion vector information are also understood to have decreasing influences as the time period of the forecast increases.

8.1 Working track minus best-track positioning differences

Our analysis of the question of reconnaissance influence on track forecast error began as a study of the differences in warning minus post-analysis best track (W-BT) positioning. Operational warning positions are the best real-time operational estimates for a cyclone's position, normally derived from the working track. A comparison of JTWC warning position vs. best track position differences should yield similar fix variations as those found for the satellite vs. aircraft position differences from the SAMC analysis. Figure 8.1 shows the mean and 90th percentile warning minus best-track positioning differences for three classes of TCs: all cyclone cases, weaker cyclones (those with 45 knot maximum winds or less), and TCs classified as recurvers. Mean warning minus best track position differences are nearly half a degree (30 n mi or 55 km) with a 10 percent chance of a positioning error of about a full degree (60 n mi or 111 km) or more. The case of "never air" refers to tropical cyclones in which aircraft observations were never available. The label "no air" represents cases where no aircraft was present in the 12-hr interval before determination of the warning position. The label "air" is the case where aircraft fix measurements were made in the 12-hour interval before the warning fix estimate.

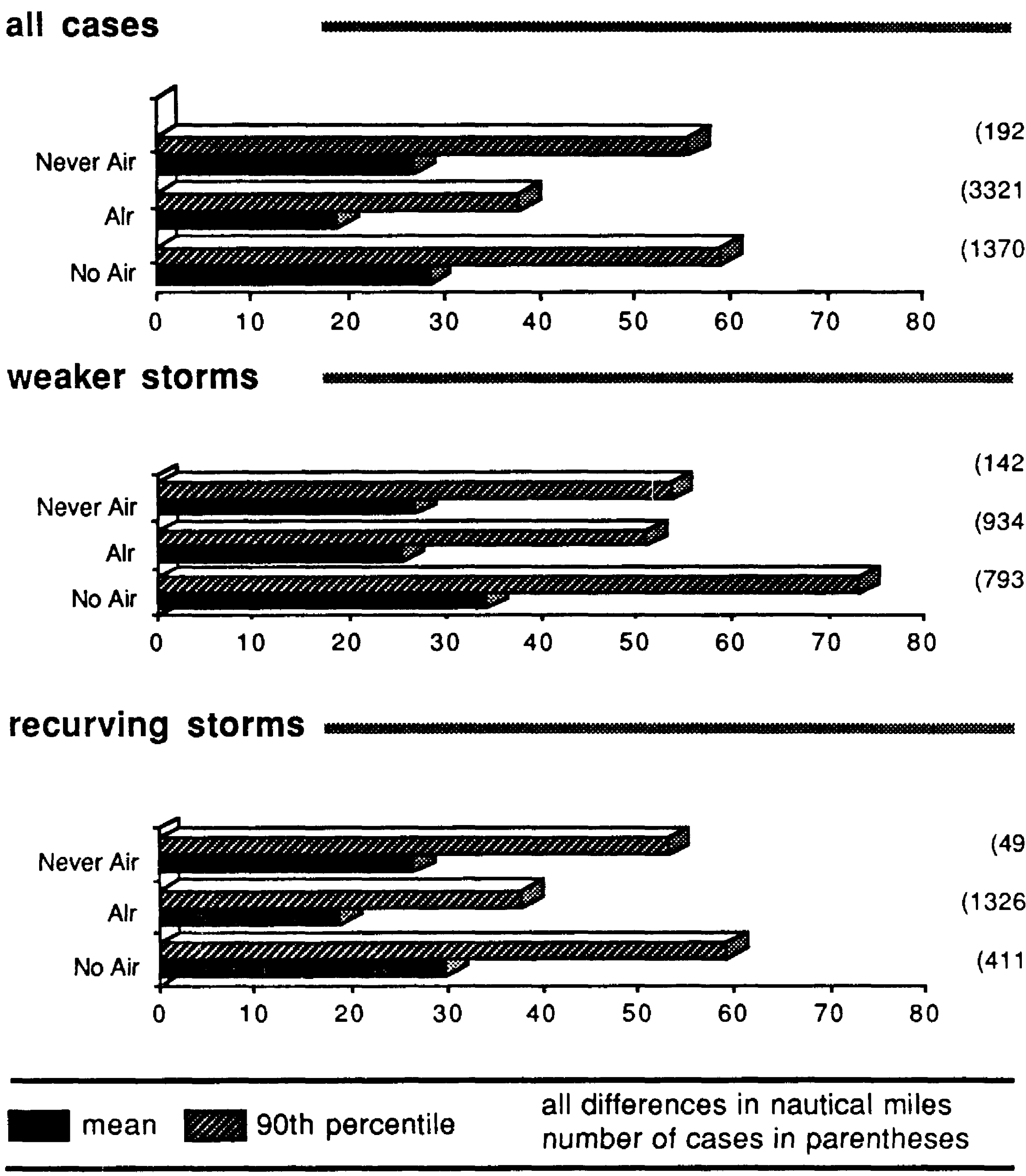


Figure 8.1: Initial TC warning minus best track (W-BT) as a function of whether aircraft were ever flown into the TC (Never Air), whether aircraft were present in the cyclone in the last 12 hours (Air) or whether aircraft were flown in a TC but not in the last 12 hours (No Air). Mean and 90th percentile values are shown. Weaker storms are those with a maximum wind speed of 45 knots or less.

Table 8.1 shows mean and 90th percentile initial position errors as a function of prior 6- and 12-hour aircraft reconnaissance for all TC cases, weaker cyclones, and recurving TCs. Little difference between TC classes is observed. Having aircraft in the prior 6-hour period slightly improved W-BTs over having aircraft in the prior 12-hour period. The mean difference between having aircraft and not having aircraft measurements was around 10 nautical miles. The 10 percent highest positioning differences for warning minus best track position between aircraft vs. no aircraft instances, are greater than 20-25 n mi.

8.2 Influence of warning minus best track positioning error on 24- to 72-hour track forecasts

Typically, for forecasts at 24 hours and beyond, the accuracy of the position fix is not as important as the accuracy of the initial TC motion vector. Table 8.2 shows the correlation coefficients of initial warning minus best track (W-BT) position error vs. the NW Pacific track forecast errors from the JTWC, the One-way Tropical Cyclone Model (OTCM), and the Climatology-Persistence model (CLIPER) forecasts. Each correlation was based on almost 3,000 forecasts. This table shows that a predominant amount of the TC forecast variance, particularly at the larger time periods, cannot be explained by initial position error (i.e., W-BT differences). Warning minus BT position errors are only weakly correlated with forecast errors at 24 hours and even less correlation is noted at 72 hours. The influence of the multiple or consecutive positioning uncertainties upon the initial TC motion vector is likely the more important feature of extended range forecast accuracy. Great subjectivity is present in the method used by the forecaster to determine the initial TC motion vector.

A question remains as to the benefits of aircraft reconnaissance in providing a superior initial motion vector. Is the motion vector obtained by successive satellite fixes of TC cloud cluster motion or other means without the aid of aircraft information just as good for forecast requirements? An answer to this question requires the determination of whether having aircraft reconnaissance can significantly improve the operational working track motion vector. For track forecasting purposes, post-analysis best tracks are usually

Table 8.1: Comparison of initial position error (warning minus best track) between various TC classifications for cases of having or not having aircraft reconnaissance 6 or 12 hours prior to the fix or never having aircraft in the TC at all. Weaker cyclones are those with maximum winds of 45 knots or less.

All Cases

	6hr interval		12hr interval	
	mean	90th%	mean	90th%
aircraft	16	31	19	38
no aircraft	26	52	28	59
never aircraft	27	55	27	55

Weaker Cyclones

	6hr interval		12hr interval	
	mean	90th%	mean	90th%
aircraft	20	41	26	51
no aircraft	34	72	34	73
never aircraft	27	54	27	54

Recurving Cyclones

	6hr interval		12hr interval	
	mean	90th%	mean	90th%
aircraft	16	31	19	38
no aircraft	26	52	30	59
never aircraft	27	53	27	53

values in nautical miles

Table 8.2: Correlation coefficients of initial TC position error (i.e., different between warning and post-analysis best track) with 24-, 48-, 72-hour JTWC-OTCM-CLIPER forecast errors.

JTWC forecast

	initial error
initial error	1
24 hour	0.145
48 hour	0.076
72 hour	0.047

OTCM forecast

	initial error
initial error	1
24 hour	0.169
48 hour	0.109
72 hour	0.080

CLIPER forecast

	initial error
initial error	1
24 hour	0.329
48 hour	0.186
72 hour	0.092

much superior to working track information. For instance, Neumann (1988—personal communication) compared the forecast errors in his Atlantic NHC-83 TC track forecast model (Neumann, 1983) for model initialization with working track fixes, with those track forecast errors in model forecasts from initialization with post-analysis best track positions. Table 8.3 shows results from his analysis. Note how much better the forecasts from the post-analysis best track were in comparison to the forecast errors resulting from the working track positions, particularly for those forecasts at 12 and 24 hours. Post-analysis best track initialization reduced forecast errors compared with those of the working track by 52 percent at 12 hours and 30 percent at 24 hours. Initialization influences were detectable out to 60 hours.

Caution is warranted here. The amount that aircraft reconnaissance may improve the TC warning track and subsequent longer range forecasts of 36 to 72 hours has not been established. Reconnaissance flights do not necessarily assure a superior working track in all cases. They do, however, significantly reduce W-BT positioning differences. As will be discussed later, Southern Hemisphere W-BT positioning differences where reconnaissance flights are not made are about double the W-BT positioning differences of the Atlantic and NW Pacific where reconnaissance has been conducted. The average short range TC

Table 8.3: Illustration of Atlantic forecast error differences which result from using post-analysis best track as compared with using working best track for the same model forecast (NHC-83). Sample size 277. (Personal information from C. Neumann, 1988.)

	Forecast Period (hours)					
	12	24	36	48	60	72
Operational Initialization	48	94	149	195	257	303
Best Track Initialization	23	66	122	172	242	298
% difference	52%	30%	18%	12%	6%	2%

values in nautical miles

track forecast up to 24 hours is improved by having reconnaissance information. But, how much the 36- to 72-hour TC track forecasts are improved through reconnaissance is another question.

8.3 Aircraft influence on JTWC official forecasts

In order to measure the impact of aircraft reconnaissance on 24- to 72-hour TC track forecasts we have examined the 6- and 12-hour time intervals before a TC track forecast was made to determine if these aircraft fixes had reduced the track forecast errors when compared with forecast cases when reconnaissance information was not available. Were forecast error statistics any different as a result of the aircraft information?

The influence on the 24-, 48-, and 72-hour track forecast error of having or not having aircraft reconnaissance in the 12 hours prior to the official NW Pacific JTWC forecast is shown in Fig. 8.2 for three classes of cyclones. Forecasts were made during the period 1979-86. Having prior 12-hour reconnaissance fixes appeared to improve the average 24-hour JTWC forecast by a small amount but did not improve the longer range 48- and 72-hour forecasts over what they would have been without reconnaissance flights. We also looked at the forecast error statistics of having or not having aircraft in the prior 6-hour period before forecasts and found little difference between the prior 6- and 12-hour periods. We thus show only the 12-hour period information in keeping with the aircraft vs. no-aircraft stratification results already discussed for the SISO analyses.

Figure 8.3 shows that a similar assessment holds for the cases of JTWC forecasts of the initially weaker intensity TCs ($V_{max} \leq 45$ kts). This is somewhat surprising because fix position errors are larger for the weaker intensity TCs. TC motion vectors of the weaker cyclones are apparently determined to a sufficient extent without benefit of reconnaissance information.

The picture is different for JTWC forecasts of recurving TCs however. Figure 8.4 shows that recurvature is somewhat better forecast when aircraft reconnaissance was available 12 hours before the forecast. Forecast differences are found out to 72 hours. A significant reduction was observed in the worst 10 percent forecast errors when reconnaissance aircraft were available before forecasts were made.

8.4 Influence of aircraft reconnaissance on One-Way Tropical Cyclone Model (OTCM) and CLIPER model forecasts

Results for OTCM, the best NW Pacific dynamic forecast model, are portrayed in Figs. 8.5 through 8.7. See JTWC (1987) for forecast model descriptions. Very similar results are obtained from similar analysis of the JTWC forecasts. A third test of the influence of aircraft data on forecast error involved comparisons with the Climatology-Persistence (CLIPER) model. Forecast errors are shown in Fig. 8.8 through 8.10. Results are again similar to those obtained with the JTWC and OTCM forecasts. Sizable forecast error reduction with 12-hour prior reconnaissance information vs. forecast error with no reconnaissance occurred only for the recurving TCs. CLIPER forecasts of the weaker intensity cyclones were even somewhat larger for situations when aircraft information was available. It is noted, however, that recurvature cases with aircraft measurements had reduced mean 72-hour CLIPER forecast errors of 50 n mi (93 km) and the worse 10 percent forecast errors by nearly 100 n mi (185 km).

8.5 Conclusions about aircraft influence on forecast accuracy

Table 8.4 presents a summary of the mean forecast error differences which occurred as a result of having reconnaissance aircraft in the 12-hr period prior to the forecast vs. not having such aircraft information. Negative values denote forecasts that were better with prior12-hour aircraft information; positive values depict worst forecasts. Note that differences are, in general, small and that significant forecast error improvement as a result of aircraft measurements occurs only in the cases of recurving cyclones. As used in the NW Pacific during this period, reconnaissance aircraft did not appear to substantially improve the working track initial TC motion vector to a degree that a superior TC track forecast was made. A particular surprise was that the initially weaker cyclones did not show even modest forecast error improvement with reconnaissance. Greater center fix uncertainties are known to exist in the weaker cyclones. This may indicate that motion vectors derived for the weaker systems from satellite observed cloud cluster movement or other means were generally as good as the motion vectors which had been derived from the more accurate aircraft determined fixes.

These results may be better understood if we accept the premise that aircraft reconnaissance fix information is generally not transformed into superior 12-hour working track motion vectors for resultant better track forecasts. Apparently the careful use of many consecutive satellite fix positions, which are judiciously smoothed, can lead to as representative a 12-hour TC motion vector as can the use of a mix of aircraft and satellite fixes.

Aircraft fix information may, at times, even lead to a worse initial motion vector. Cyclone centers frequently have irregular and oscillatory motion not representative of the conservative time-average motion desired for the forecast products. Tracking of the TC's cloud envelope possibly gives as conservative an estimate of TC motion as the tracking and attempted smoothing of unrepresentative large jerks and jumps of TC center motion from more accurate aircraft fixes. Such small scale TC motions are not representative of the longer period average TC motion vector desired by the forecast models. This may help explain why so little difference was noted in the TC track forecasts of cyclones with and without 12-hr prior reconnaissance information.

The reader must realize that this discussion applies only to the long period average track forecast. In many individual forecast situations aircraft information may have lead to distinctly superior forecasts. Of course, for the short-range (time < 24 hours) predictions necessary for accurate landfall forecasts, the aircraft's distinct advantage in providing assured accurate fix positions becomes as or more crucial than obtaining a smooth motion vector.

8.6 Other likely benefits of aircraft reconnaissance for TC track prediction

Other aspects of the TC track forecast question should be considered. If used to fly synoptic track missions, aircraft may augment observations in crucial data void ocean regions around the cyclone and improve knowledge of the TC's environmental steering current which should produce superior TC track forecasts. The role of aircraft reconnaissance for TC track forecasting should not be thought of exclusively as a tool for better center fix determination. A number of TC experts are of the opinion that the full value of aircraft reconnaissance often has not been realized. Many forecasters have been reluctant to abandon the tasking of the traditional, routine center fix missions for the potentially more important surrounding cyclone synoptic missions. Synoptic missions, for instance, on the poleward side of the TC can indicate the general strength and the changes in character of the subtropical ridge. This knowledge can frequently lead to the improvement of the recurvature forecast and/or turning track motion—the really difficult and important track forecasts. Synoptic flight tracks in the Atlantic have tended to improve TC track forecast accuracy in those cases where they were made. More forecast track improvement in the NW Pacific may have resulted had the aircraft been flown more frequently in the synoptic role rather than in the center fix mode.

Reconnaissance aircraft probably can be used to help smooth out the oscillatory motion of the TC eye by measuring changes in the TC inner-core mean vortex wind and symmetric height fields of the cyclone's mass-flow envelope as discussed by Sheets (1985, 1986). Center tracking of the average inner-core wind vortex and height-field likely is more representative of the TC's longer period conservative motion vectors. These conservative motion vectors are needed for track extrapolation and for improved track forecasts.

New TC motion research (Chan and Williams, 1987, Holland, 1983) is showing a varying influence of TC outer-core (100-300 km radius) vortex wind strength on the motion deviation of TC from its environmental steering current. A strong TC outer-core (i.e. 100-300 km) circulation has a greater northwestward Beta-motion drift than do weaker outer-core strength TC vortices of the same central pressure. Aircraft can directly measure outer vortex circulation strength while the satellite, because of upper cloud contamination, is unable to trace middle level cloud motion.

It is to be expected that numerical and empirical TC track forecast schemes would be improved when and if outer-core TC vortex circulation strength is incorporated into operational TC forecast track schemes. Outer-core wind strength measurements also give reliable information of 30 and 50 knot wind radii.

The merits of TC reconnaissance for track forecasting should not be judged exclusively on the role which NW Pacific TC reconnaissance played in the past. A number of improvements in the reconnaissance aircraft measurement capability and in the mode of aircraft operation may help in improvement of TC track forecasting.

More important than all these considerations, however, is the issue of aircraft reconnaissance influences on reducing forecast errors associated with the occasional large satellite position fix inaccuracy. The redundancy of having both satellite and aircraft data adds reliability to TC forecasts. Aircraft may help prevent the occasional large forecast error by maintaining an important ground-truth TC information source.

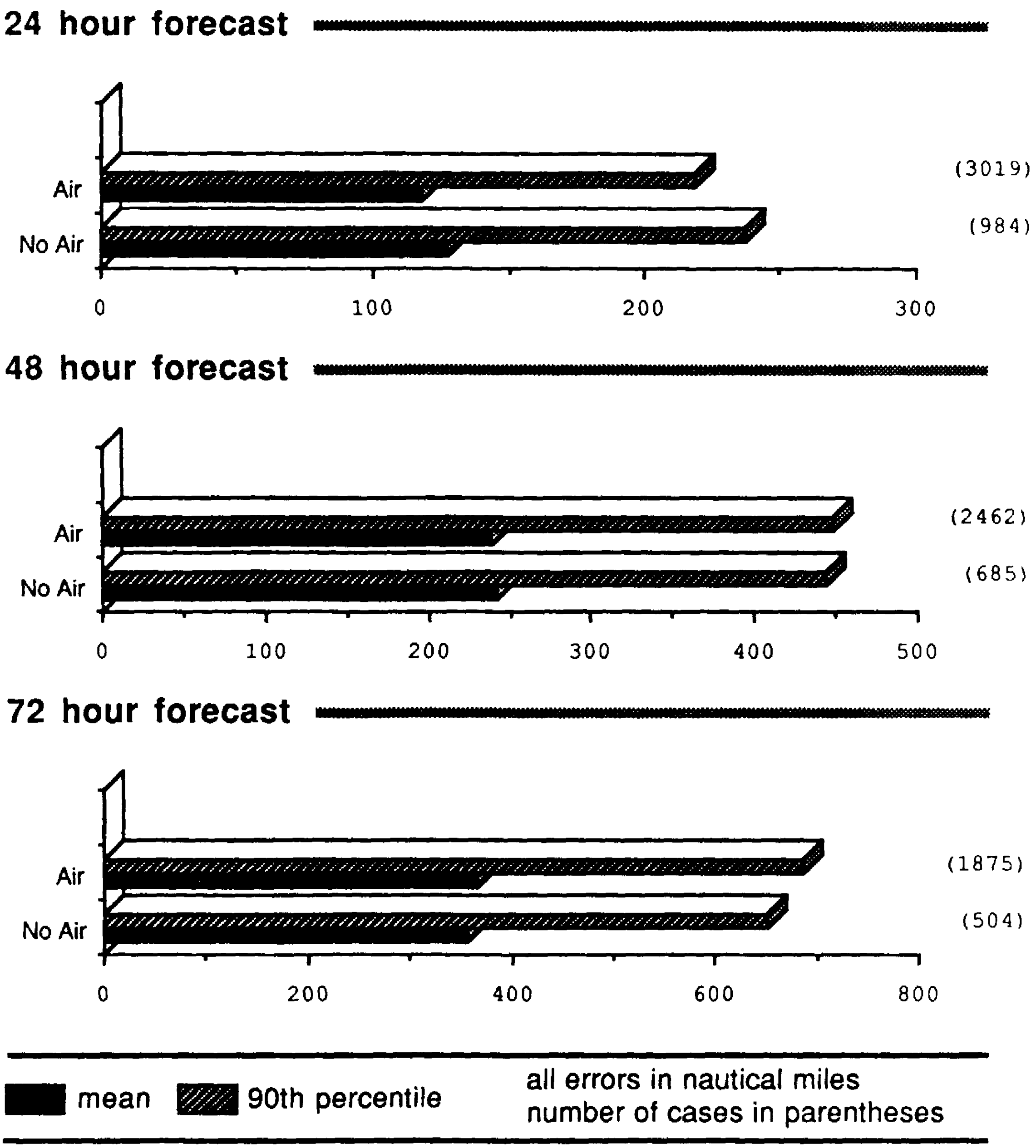
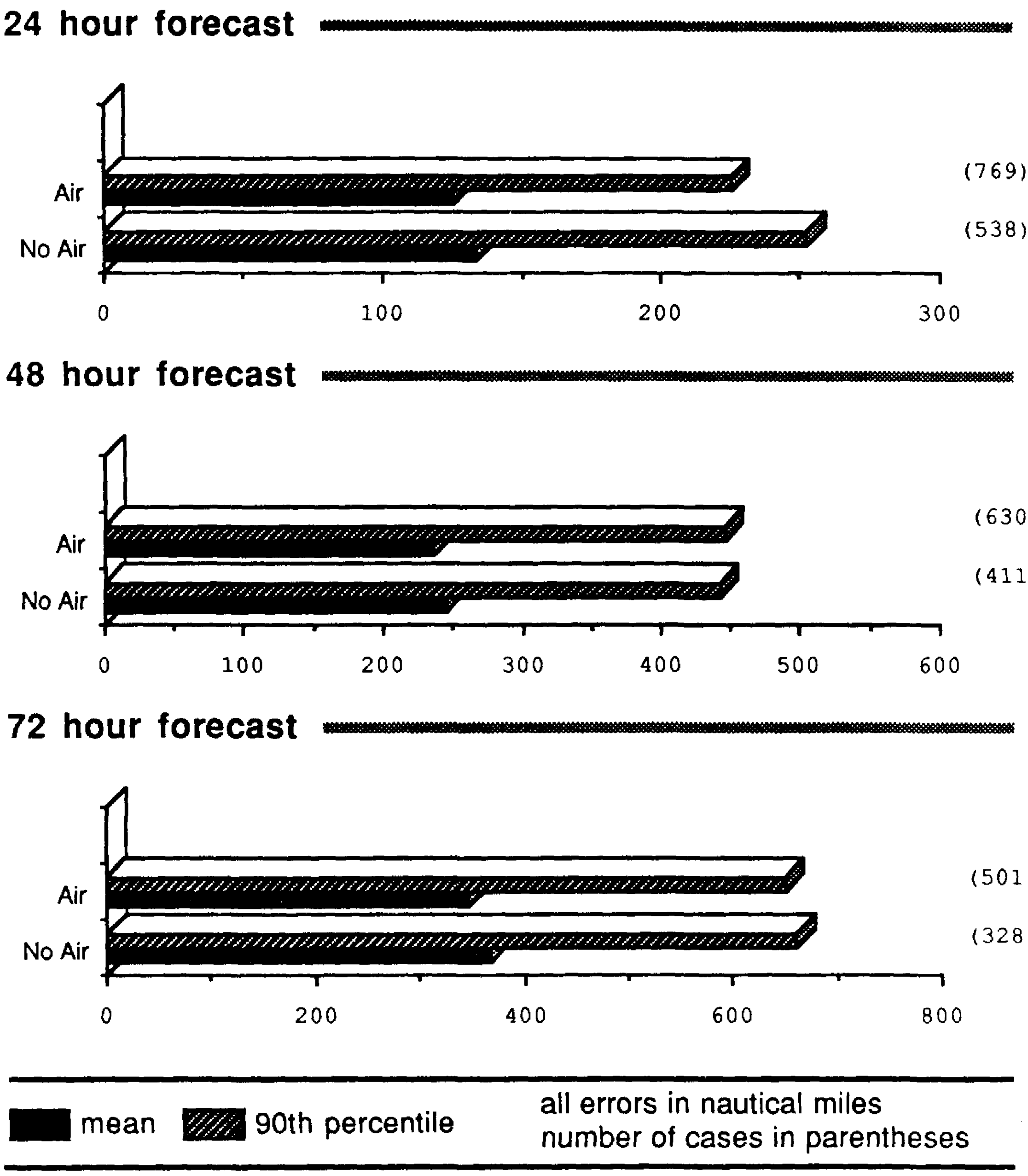


Figure 8.2: Joint Typhoon Warning Center (JTWC) forecasts for all TC cases of the influence of having reconnaissance aircraft present in the 12-hr period before the forecast was made (Air) as compared with not having aircraft in the prior 12-hr period (No Air). Mean and 90th percentile forecast errors are given. Number of cases is in parentheses on the right.



24 hour forecast

48 hour forecast

72 hour forecast

all errors in nautical miles
number of cases in parentheses

Figure 8.3: Same as Fig. 8.2 except for JTWC forecast of initially weaker intensity cyclones ($V_{max} \leq 45$ kts).

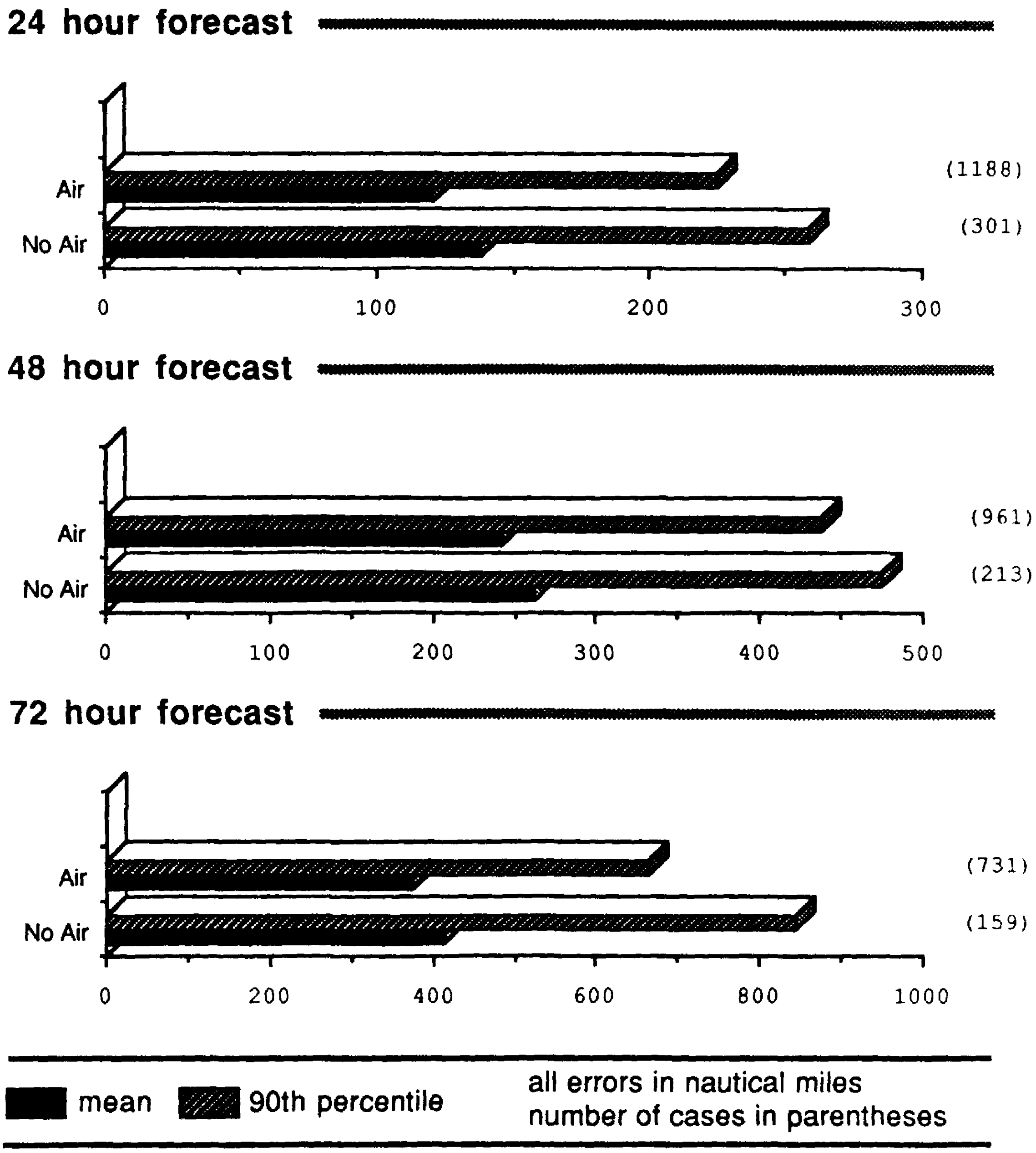


Figure 8.4: Same as Fig. 8.2 except for JTWC forecast of recurving cyclones ($V_{max} \leq 45$ kts).

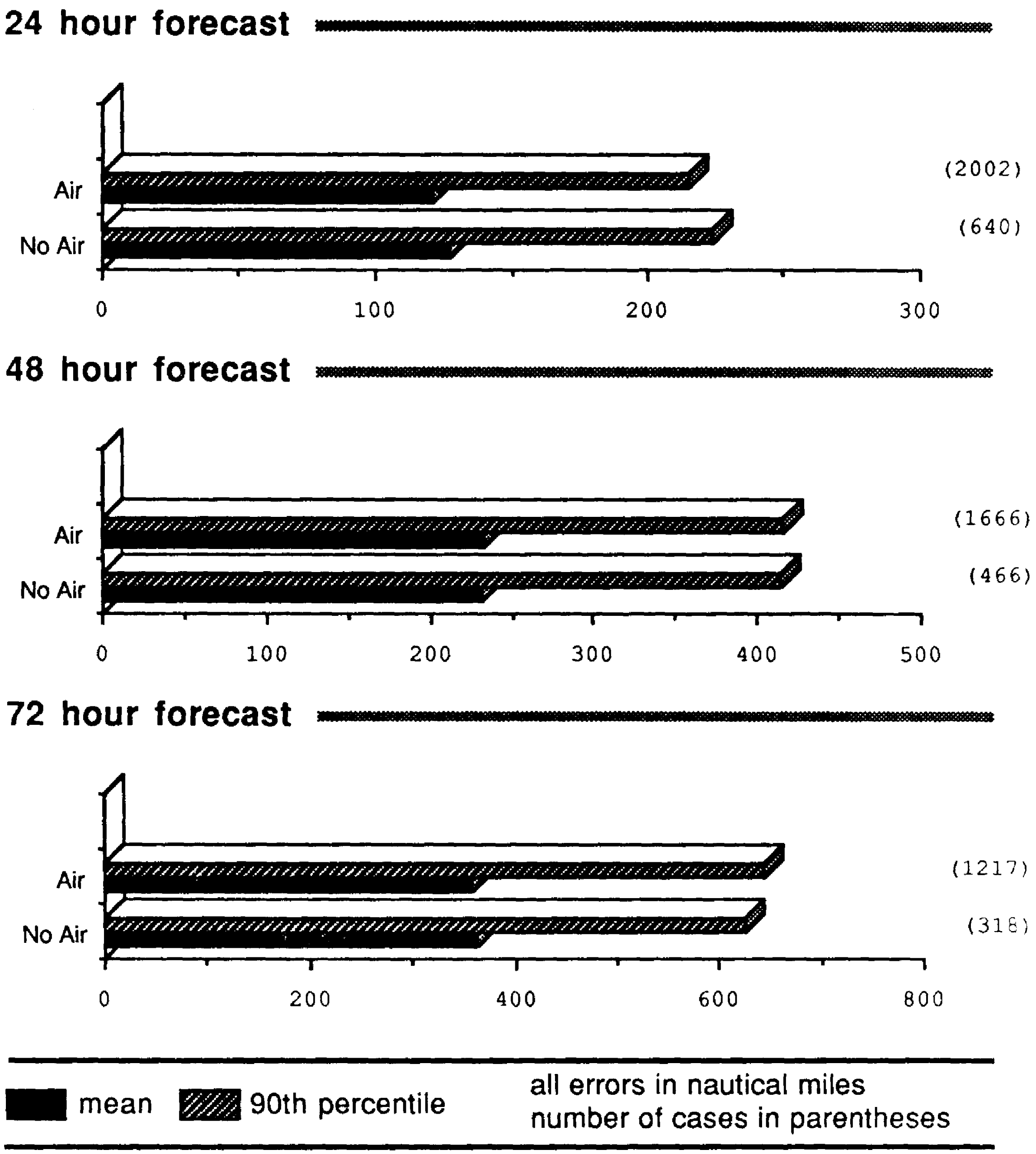


Figure 8.5: Same as Fig. 8.2 except for One-Way Tropical Cyclone Model (OTCM) forecasts.

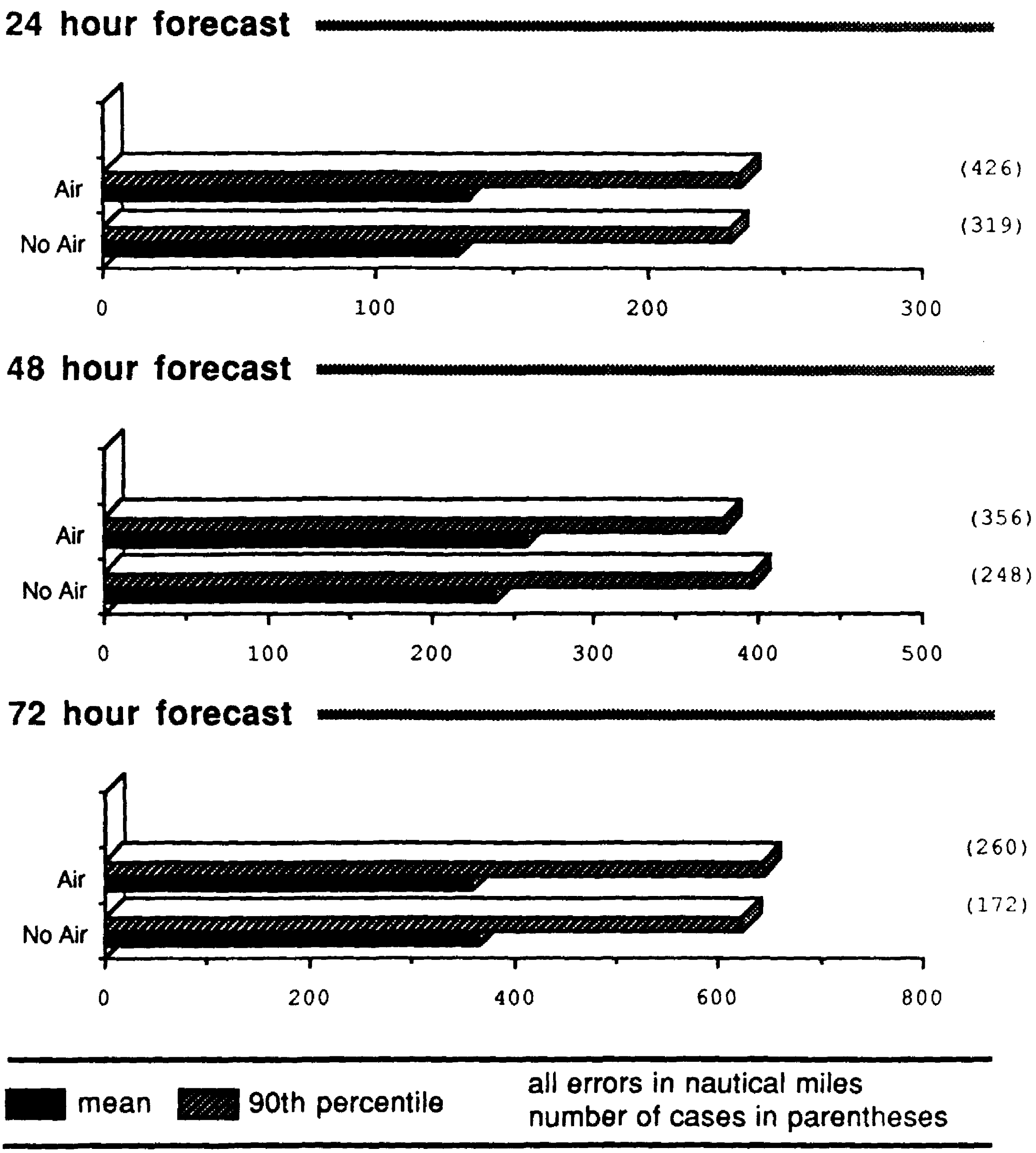


Figure 8.6: Same as Fig. 8.2 except for OTCM forecast of initially weaker intensity cyclones ($V_{max} \leq 45$ kts).

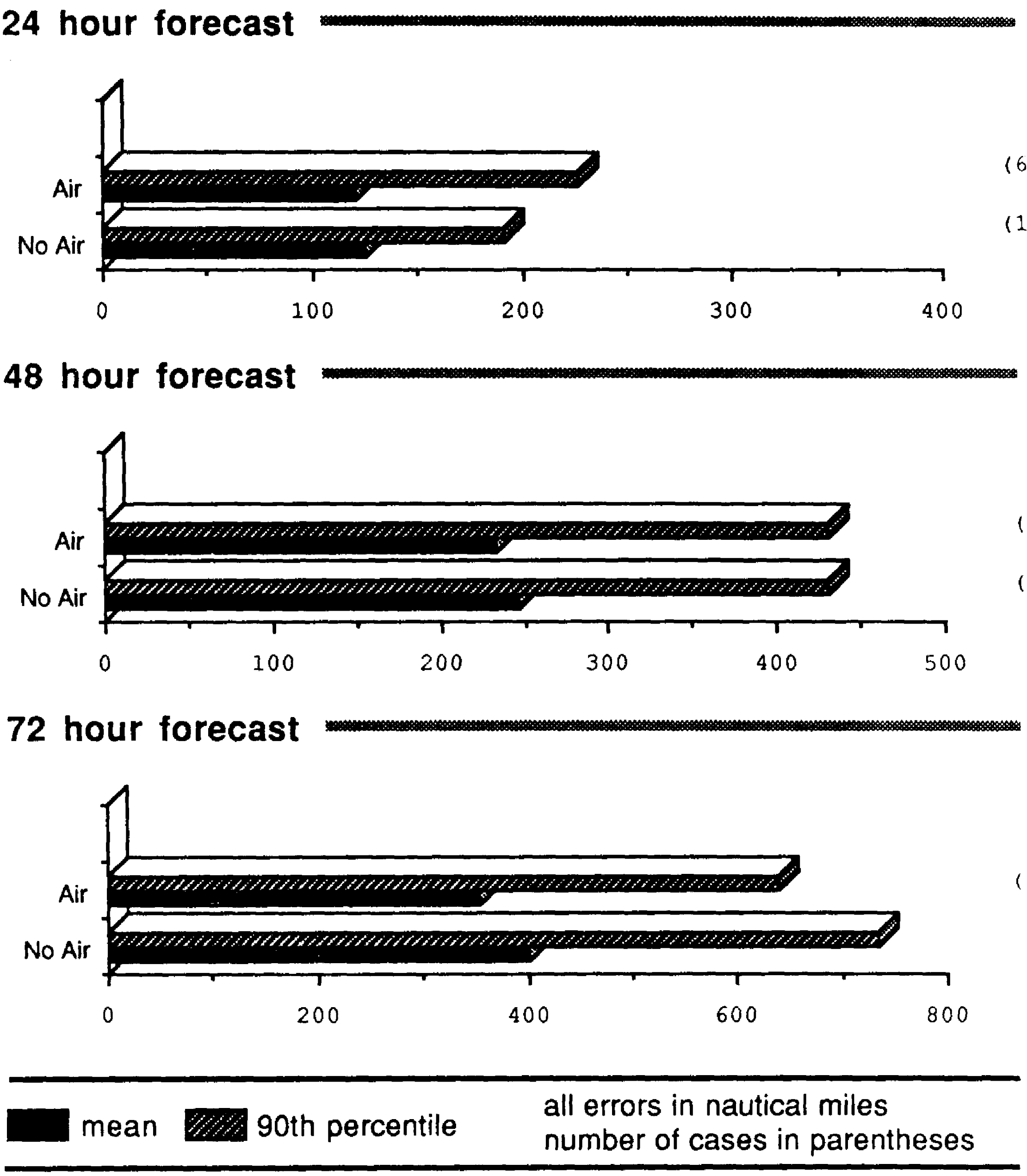


Figure 8.7: Same as Fig. 8.2 except for OTCM forecasts for recurving TCs.

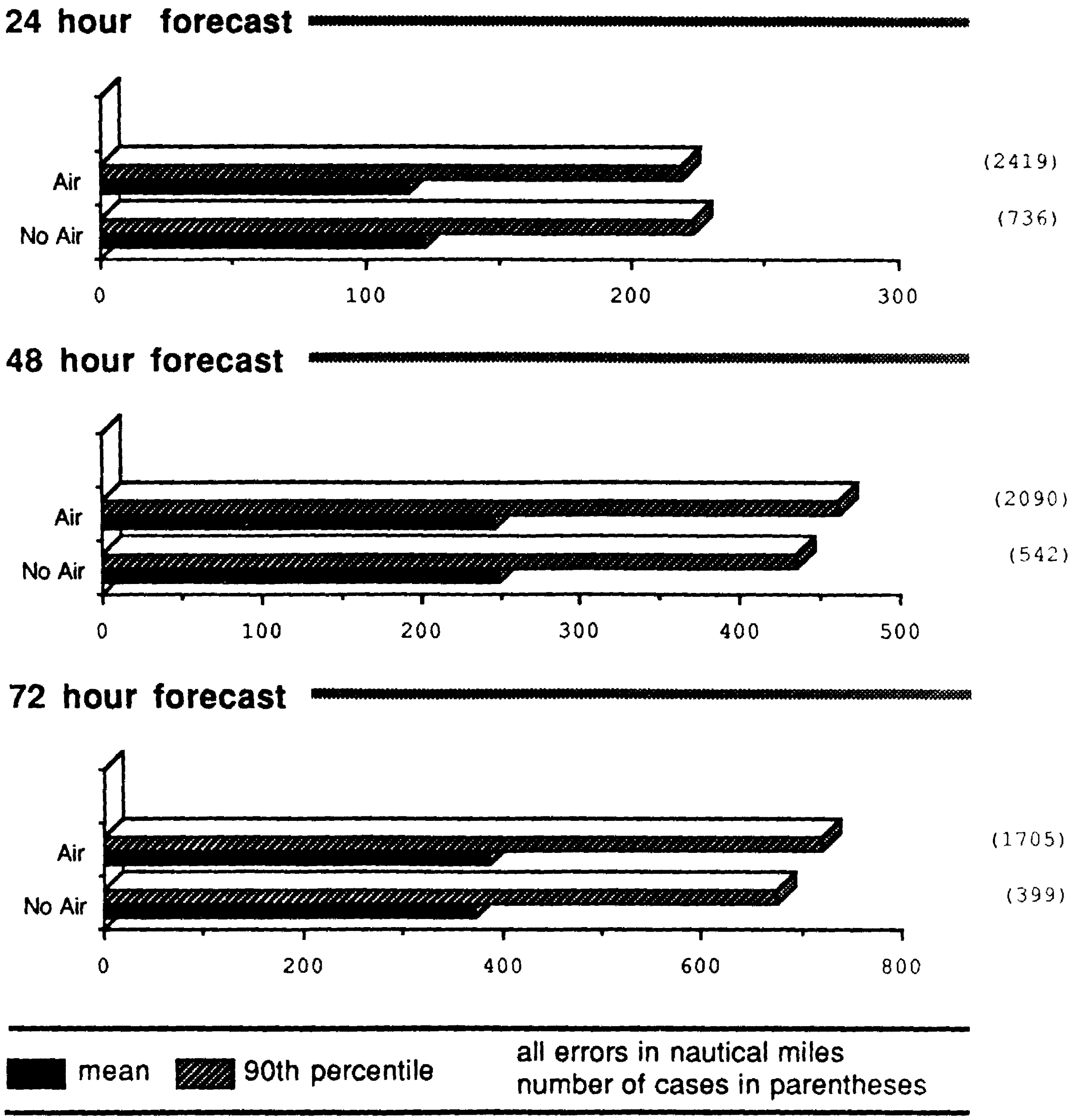


Figure 8.8: Same as Fig. 8.2 except for Climatology-Persistence (CLIPER) model forecasts.

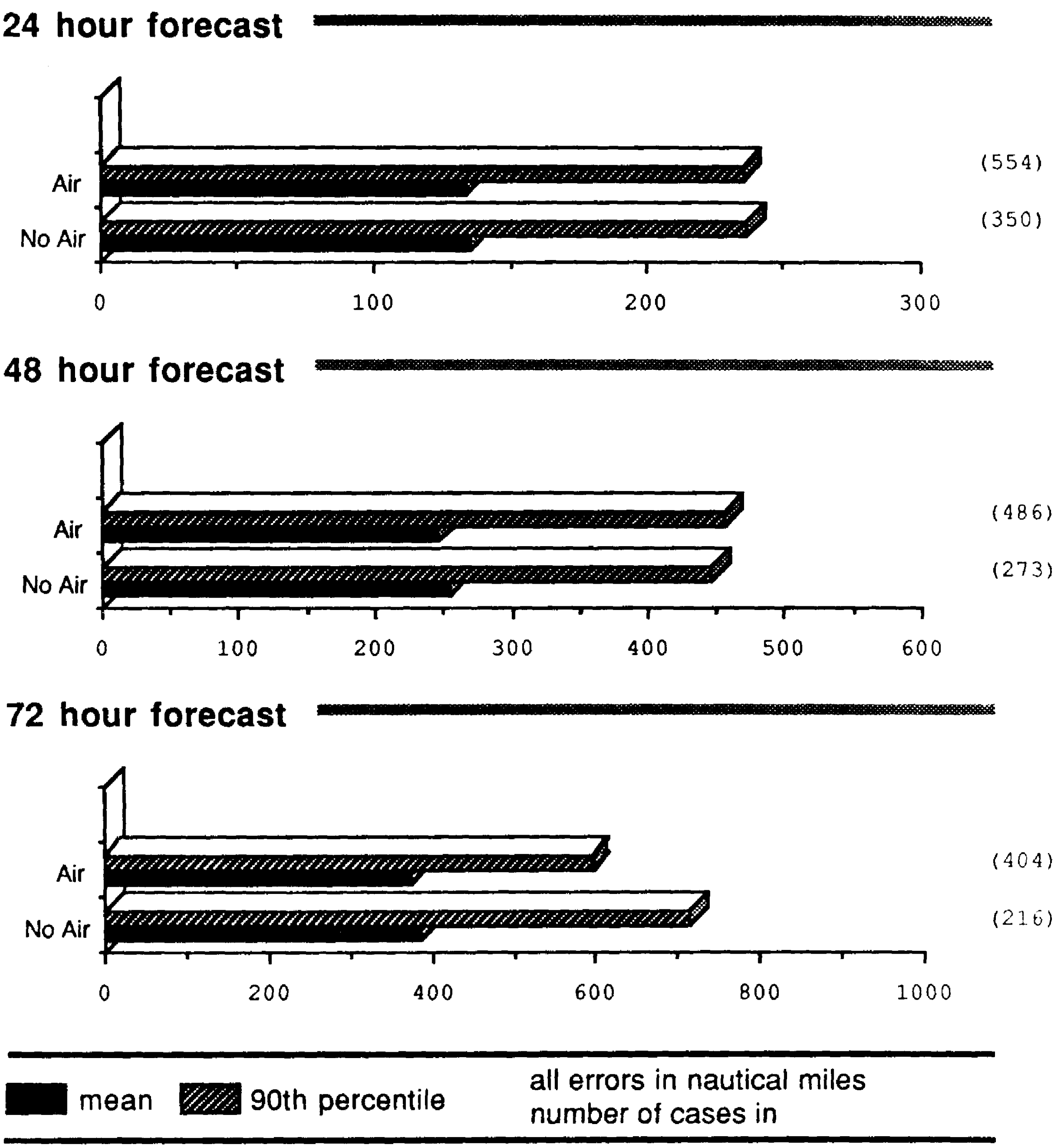


Figure 8.9: Same as Fig. 8.2 except for CLIPER forecasts of initially weaker intensity ($V_{max} \leq 45$ kts) TCs.

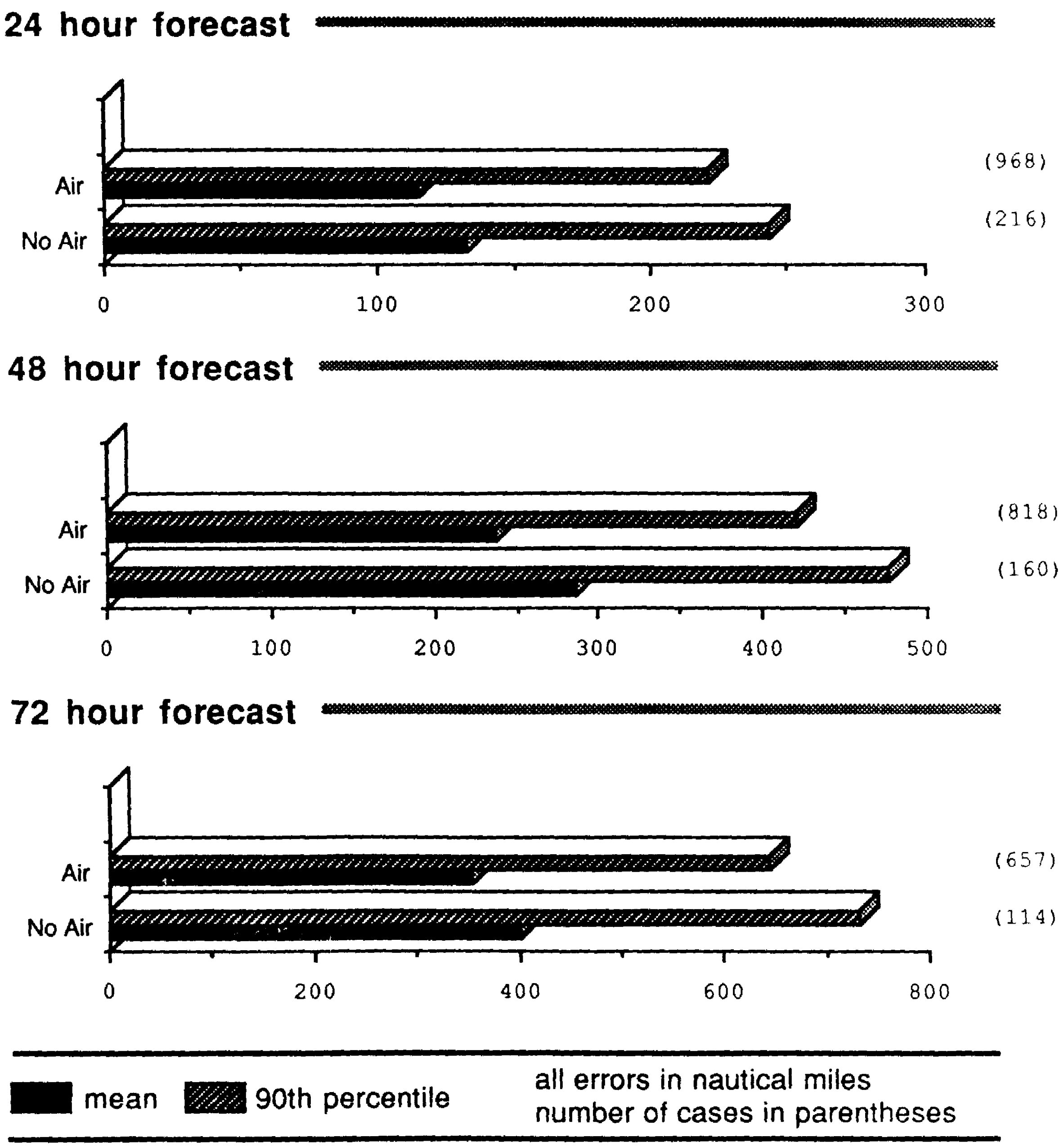


Figure 8.10: Same as Fig. 8.2 except for CLIPER forecasts of weaker intensity cyclones ($V_{max} < 45$ kts) TCs.

Table 8.4: Comparison of 24-, 48-, 72-hour forecast error differences occurring in various forecast schemes for cases in which aircraft position was made in the 12 hours prior to forecast minus those cases in which aircraft was not available in the prior 12-hour period. Negative values mean the forecasts were better with aircraft information. Mean and 90th percentile differences are shown.

24 hour forecasts

		JTWC	OTCM	CLIPER
all cyclones	mean	-9	-6	-6
	90th%	-18	-9	-5
weaker cyclones	mean	-7	9	-2
	90th%	-20	5	-1
recurving cyclones	mean	-18	-5	-18
	90th%	-33	35	-21

48 hour forecasts

		JTWC	OTCM	CLIPER
all cyclones	mean	-3	2	-3
	90th%	4	2	28
weaker cyclones	mean	-13	24	-6
	90th%	9	45	12
recurving cyclones	mean	-21	-14	-48
	90th%	-36	0	-56

72 hour forecasts

		JTWC	OTCM	CLIPER
all cyclones	mean	9	-6	15
	90th%	36	18	46
weaker cyclones	mean	-19	-4	-16
	90th%	-13	16	-123
recurving cyclones	mean	-38	-47	-46
	90th%	-178	-94	-88

errors in nautical miles

Chapter 9

COMPARISON OF NW PACIFIC RESULTS WITH RELATED STUDIES FROM OTHER TC STORM BASINS

Related recent studies on this subject in other TC ocean basins show general agreement with these results. The most relevant recent studies are those of Sheets and McAdie (1988) and McBride and Holland (1987). An earlier, and particularly relevant, study was that of Sheets and Grieman (1975).

9.1 Comparison of warning minus best track position differences

This study and the recent Sheets and McAdie investigation do not agree with the optimistic views of Gaby *et al.* (1980) on the general improvement in satellite measured fix accuracy. The Gaby, *et al.* study determined TC fix accuracy based on average differences between satellite fixes and best track. We found no confirmation of a continuing improvement trend in satellite derived fix accuracy over best track in the 1979-86 period in the NW Pacific. Likewise, no improvement trend in satellite fix capability was found by Sheets and McAdie (1988) for more recent Atlantic and NE Pacific data.

Table 9.1 shows a comparison of the Gaby *et al.* 1970's fix results with those of Sheets and McAdie (1988) and this study for the 1980's. Note that Sheets and McAdie's Atlantic operational satellite position differences from best track in the 1980's are 24 percent larger than Gaby *et al.*'s last 5 years of Atlantic position differences in the late 1970's. And the standard deviation of differences was 30 percent greater. The mean and standard deviation of NW Pacific fix differences of this study are 37 and 35 percent larger than the Gaby, *et al.* values. Satellite technology of the 1980's is surely not worse than it was in the late

1970's. The Gaby, *et al.* study does not appear to be a realistic assessment of late 1970's satellite center fix accuracy.

Table 9.1: Comparison of mean and standard deviation differences in warning vs. best track position fix differences of this and Sheets and McAdie's study with the last 5-year average of the Gaby, *et al.* study.

Gaby, et.al. (1980)	mean	standard deviation
1971	36	na
1972	33	17
1973	26	19
1974	18	16
1975	17	11
1976	17	14
1977	16	15
1978	17	17
1974-1978 average	17	15
Sheets and McAdie (1988)		
1981-1986 average	21	19
% greater than Gaby, et.al.	24%	30%
this study		
NW Pacific 1979-86	22	26
% greater than Gaby, et.al.	29%	78%

values in nautical miles

Table 9.2 lists recently available information on mean warning minus best track (W-BT) position fix differences. Much of this has been compiled from the McBride and Holland (1987) article where they gathered information from other forecast offices. Observe the rather wide spread of reported W-BT position differences. Note the near uniformity of Southern Hemisphere (W-BT) position differences of 35-40 n mi. This might be expected in regions where aircraft reconnaissance is not available and application of satellite technology may not as advanced as in the Atlantic and NW Pacific. The Southern Hemisphere also has many island and land stations to offer superior post-analysis ground-truth to the best track determination which are not available in the northeast Pacific. This analysis leads us to question the earlier Guam reports of W-BT fix differences of but 12 and 13 n mi (22-24 km). Note that the mean NW Pacific position mean fix errors of this study are significantly larger (22 n mi - 41 km). Without aircraft W-BT positioning differences were 28 n mi (52 km). This is probably more representative of the type of warning minus best track position (W-BT) errors one should expect in situations where aircraft reconnaissance is not available.

Figure 9.1 compares the average of all three Southern Hemisphere W-BT position differences with the NW Pacific and Atlantic information (top diagram). This nearly 2 to 1 difference in W-BT position differences is believed to be largely the result of the contribution of reconnaissance aircraft in the Atlantic and NW Pacific. By contrast, much smaller NE Pacific W-BT position differences reported by Sheets and McAdie compared with the Southern Hemisphere values are likely the consequence of no supplementary surface ground truth information in the NE Pacific such as is available from the many islands and land stations in the Southern Hemisphere. The satellite is virtually the only tracking source in the NE Pacific. In this situation the best track, must of necessity, tend to collapse upon the warning track.

The improvement of W-BT positioning differences when only satellite data is available should not be interpreted as indicating that the satellite necessarily gives very accurate warning tracks.

The method of best track determination is, of course, always subject to a degree of variation in the different basins. Bell (1980) has showed that with varying reconnaissance, radar, and satellite fix information the best track itself can have different degrees of variations and uncertainties.

Table 9.2: Comparison of mean and standard deviation (in parentheses) of center fix position differences of warning to post-analysis position difference as reported by various groups.

Difference of TC Warning Minus Best Track Position

NW Pacific 1979-86 all cases (this study)	22 (26)
NW Pacific 1979-86 with aircraft (this study)	19 (20)
NW Pacific 1979-86 without aircraft (this study)	28 (35)
NW Pacific 1987 op eval with aircraft (JTWC)	18 (22)
NW Pacific 1987 op eval without aircraft (JTWC)	25 (23)
NW Pacific-Japan TOPEX (McBride & Holland)	14 (16)
NW Pacific-Hong Kong 1975-82 (McBride & Holland)	20 (20)
NW Pacific-Phillipines 1980-84 (McBride & Holland)	24 (na)
NW Pacific-Guam* 1972-84 (McBride & Holland)	13 (na)
NW Pacific-Guam* 1981-85 (BMRC)**	12 (na)
NE Pacific-SFO 1986 (Sheets & McAdie)	22 (19)
Atlantic 1981-86 Miami (Sheets & McAdie)	21 (19)
Atlantic 1981-86 AFGWC (Sheets & McAdie)	32 (21)
Atlantic 1967-76 (McBride & Holland)	23 (na)
Atlantic 1976-85 (McBride & Holland)	19 (na)
Atlantic 1974-78 average (Gaby, et.al.)	17 (15)
Australia 1970-79 (McBride & Holland)	37 (na)
S Pacific & S Indian 1982-84 (BMRC)**	38 (na)
Southern Hemisphere 1980-84 (NOCC/JTWC)	40 (na)

values in nautical miles

** Guam (JTWC) response to questionnaire*
*** Bureau of Meteorology Research Center (Australia)*

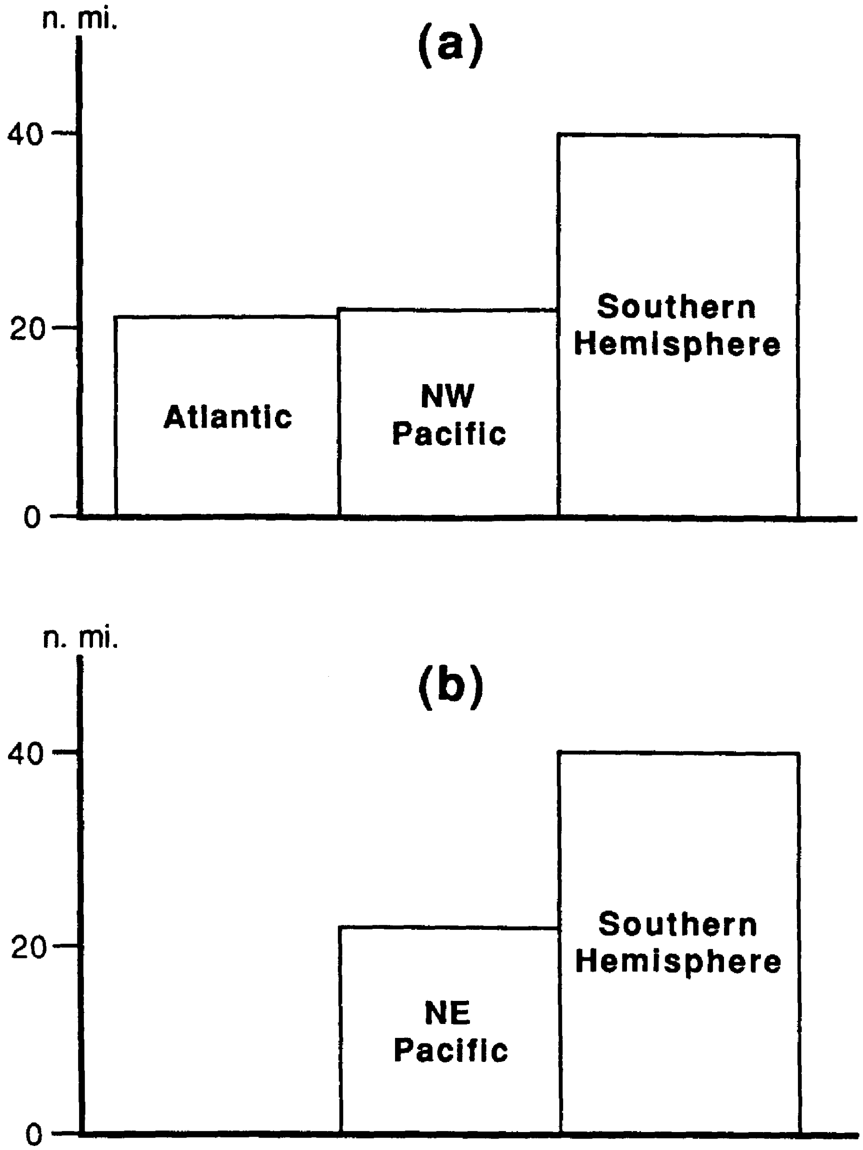


Figure 9.1: Comparison of average of three Southern Hemisphere warning minus best track (W-BT) positioning differences with those of the Atlantic and NW Pacific where aircraft reconnaissance was taken (diagram a). Comparison of average warning minus best track (W-BT) position differences in the Southern Hemisphere and with those of the northeast (NE) Pacific.

9.2 Warning minus best track positioning differences as a function of TC intensity

Table 9.3 compares W-BT in the NW and NE Pacific and in the Atlantic for the three TC intensity categories of Tropical Depression (TD)—less than 34 knot maximum winds; Tropical Storm (TS)—34-63 knot maximum wind speeds; and Typhoon or Hurricane intensity (TY/HUR)—over 63 knots maximum wind speed. As expected, W-BT differences are smaller for the more intense cyclones. Although some small differences exist between basins, results are very similar for TCs of comparable intensity.

Table 9.3: Comparison of mean and standard deviation (in parentheses) of center fix position differences (in n mi) of TC warning minus best track (W-BT) as a function of TC intensity - TD (Tropical Depression), TS (Tropical Storm), and TY/HURR (Typhoon/Hurricane).

Difference of TC Warning Minus Best Track Position

	TD	TS	TY/ HUR
NW Pacific 1979-86 all cases (this study)	32 (33)	25 (28)	15 (18)
NW Pacific 1979-86 with aircraft (this study)	29 (27)	22 (20)	14 (18)
NW Pacific 1979-86 without aircraft (this study)	36 (39)	30 (38)	17 (13)
NE Pacific-SFO 1986 (Sheets & McAdie)	24 (22)	26 (22)	14 (12)
Atlantic 1981-86 Miami (Sheets & McAdie)	23 (19)	22 (19)	19 (19)
Atlantic 1981-86 AFGWC (Sheets & McAdie)	36 (25)	34 (23)	26 (17)

values in nautical miles

9.3 Comparison of SAMC and W-BT positioning differences

Satellite warning minus best track (W-BT) mean fix position differences are in very good agreement with the Satellite and Aircraft Measurement Comparison (SAMC) results. Table 9.4 shows satellite minus aircraft track fix differences for these three TC intensity categories. Note how close the W-BT positioning differences of Fig. 9.2 are to the SAMC positioning differences of Table 9.4. Although the NW Pacific was the only basin for which a direct satellite and aircraft fix comparison (SAMC type results) was made, these SAMC results would likely be very similar in the Atlantic, the only other TC basin where aircraft reconnaissance is made and where SAMC measurements could be made. The Sheets and McAdie study well supports this conclusion.

Table 9.4: Mean and standard deviation (in parentheses) of Satellite and Aircraft Measurement Comparison (SAMC) of TC position fix differences as a function of TC intensity.

SAMC for TC position fix

	TD	TS	TY/ HUR
NW Pacific 1980-86 (this study)	37 (30)	27 (24)	17 (17)

values in nautical miles

Remember that SAMC positioning differences are computed from the differences in satellite and aircraft specified TC tracks. W-BT positioning differences appear to be largely a function of satellite–determined fix inaccuracies.

9.4 SISO fix differences

How do these W-BT and SAMC fix differences compare with those of the Simultaneous Independent Satellite Observation (SISO) fix positioning differences by TC intensity category? Table 9.5 shows a comparison for these SISO fix differences for the NW and NE Pacific and for the Atlantic. Note that SISO fix differences of this and the Sheets and McAdie study are about the same in all three TC basins. These satellite vs. satellite estimates appear to best demonstrate the accuracy limits of the present day satellite information without auxiliary observational support. Note again that these SISO fix differences are reduced by about 30 percent in cases where reconnaissance was made

12 hours before the SISO determination. Also, note the larger position fix differences at night.

Table 9.5: Mean and standard deviation (in parentheses) of TC position fix differences from Simultaneous Independent Satellite Observations (SISO) for three TC intensity classes.

SISO comparison of TC position fix

	T D	T S	TY/ HUR
NW Pacific 1979-86 all cases (this study)	40 (36)	33 (27)	20 (18)
NW Pacific 1979-86 no aircraft (this study)	41 (38)	37 (32)	23 (20)
NW Pacific 1979-86 with aircraft (this study)	37 (30)	27 (18)	17 (15)
NW Pacific 1979-86 day only (this study)	39 (35)	32 (27)	19 (17)
NW Pacific 1979-86 night only (this study)	52 (42)	38 (28)	24 (21)
NE Pacific 1986 (Sheets & McAdie)	47 (36)	39 (36)	27 (17)
Atlantic 1981-86 (Sheets & McAdie)	45 (35)	38 (27)	28 (20)

values in nautical miles

Table 9.6 gives an estimate of the expected SISO fix differences in the NW Pacific with and without aircraft reconnaissance and for day and night conditions for three classes of TC intensity. We believe that these estimates are also valid in the other TC basins. Note how much difference occurs in the positioning fixes of independent satellite observers when aircraft are not flown and at night. Mean SISO nighttime typhoon fix differences without aircraft data are 28 n mi (52 km). Mean and highest 15 percent fix differences for tropical storm and tropical depressions rise to values of 44/88 n mi (81/163 km) and 55/102 n mi (102/189 km).

Discussion. An unavoidable degree of satellite TC positioning uncertainty is frequently present. New satellite technologies will probably not significantly improve this warning fix determination in the next few years. While new image looping animation and improved IR image enhancement will probably improve future fix determinations,

Table 9.6: Mean and lower limit of 15 percent largest position differences of the Simultaneous Independent Satellite Observations (SISO) as a function of day-night and whether aircraft reconnaissance was flown in the 12-hour period before the observation. NW Pacific data from 1979-1986.

Estimated Position Fix Uncertainty

	TD		TS		TY/ HUR	
Daytime with aircraft	37	(68)	27	(49)	16	(31)
Daytime no aircraft	41	(81)	37	(75)	22	(42)
Nighttime with aircraft	49	(86)	32	(55)	20	(37)
Nighttime no aircraft	55	(102)	44	(84)	28	(50)

values in nautical miles

especially in individual cases, these improved techniques are not likely to make major improvements in TC fix accuracy over present capabilities. These newer satellite technologies have been employed in the Atlantic in recent years, yet Atlantic basin fix skill is not significantly better than those of the NW Pacific. There has also been little, if any, recent year improvement in the Atlantic.

Chapter 10

SYNTHESIZED VIEW OF AIRCRAFT INFLUENCE ON SATELLITE POSITIONING AND INTENSITY

Perhaps the most reliable assessment of how consistent satellite measurements are, without aircraft information, is given by the simultaneous estimates of TC position by two independent satellite observers (SISO observations). We can determine how the SISO fix positions vary in situations when reconnaissance data were and were not available.

10.1 Aircraft influence on TC positioning differences

Fix differences become smaller when aircraft data are available for the SISO estimates in comparison to those situations when aircraft reconnaissance is not available. SISO information may thus help us calibrate the influence of the aircraft data on the satellite position measurement. SISO data may also help us isolate the influence of the aircraft on the SAMC positioning differences.

Figures 10.1 and 10.2 show mean and mean plus one standard deviation of SISO fix position differences with and without aircraft fixing in the previous 12 hours (top diagrams of each figure). We attribute the smaller SISO position differences with the aircraft-induced position bias. Note that the aircraft measurements have reduced the SISO fix differences by about one quarter.

These aircraft induced SISO position reductions agree with the satellite minus aircraft SAMC fix differences as indicated by the middle diagram of these figures. Also, note how similar the working minus best track (W-BT) position differences are between the no–aircraft and the with–aircraft information (bottom diagrams) as compared with the middle and top diagrams.

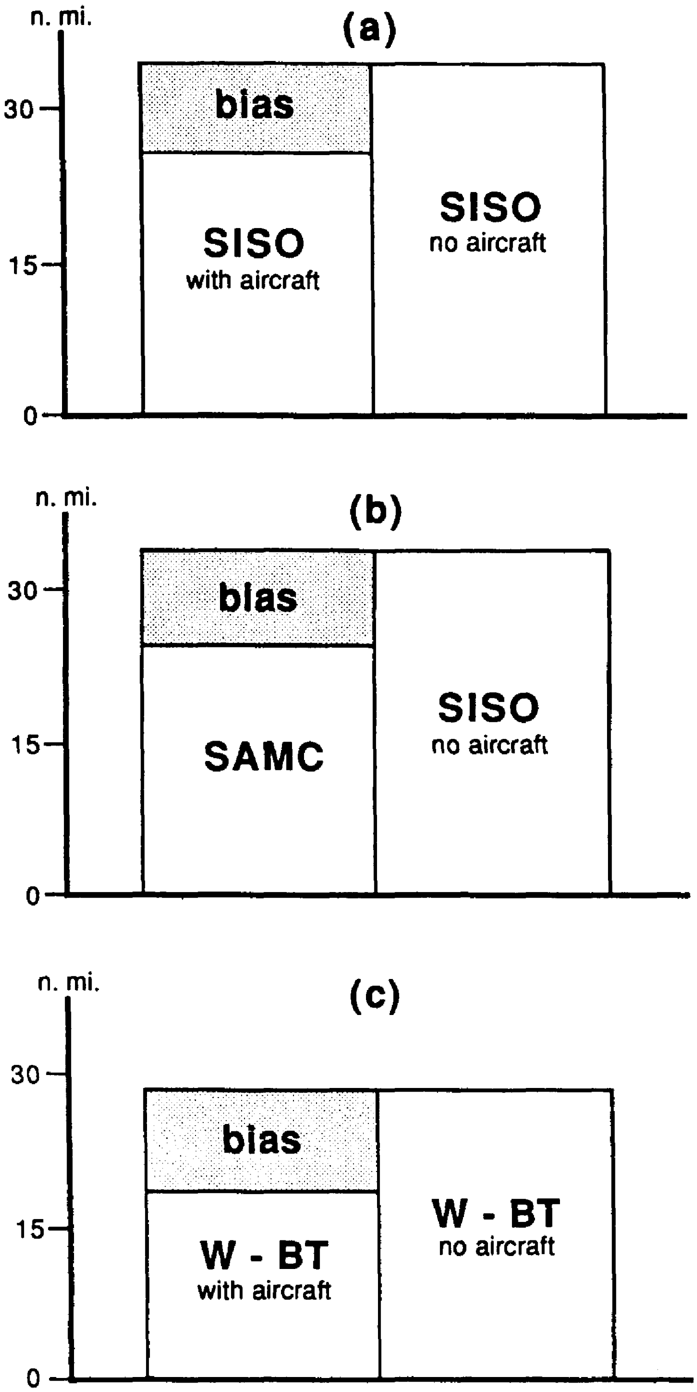


Figure 10.1: Comparison of mean NW Pacific 1979-86 positioning fix differences between situations when aircraft fixes were made in the prior 12-hour period (left side of diagrams) to those cases when no aircraft flights were made in this period (right side of diagrams). Shaded area indicate aircraft bias.

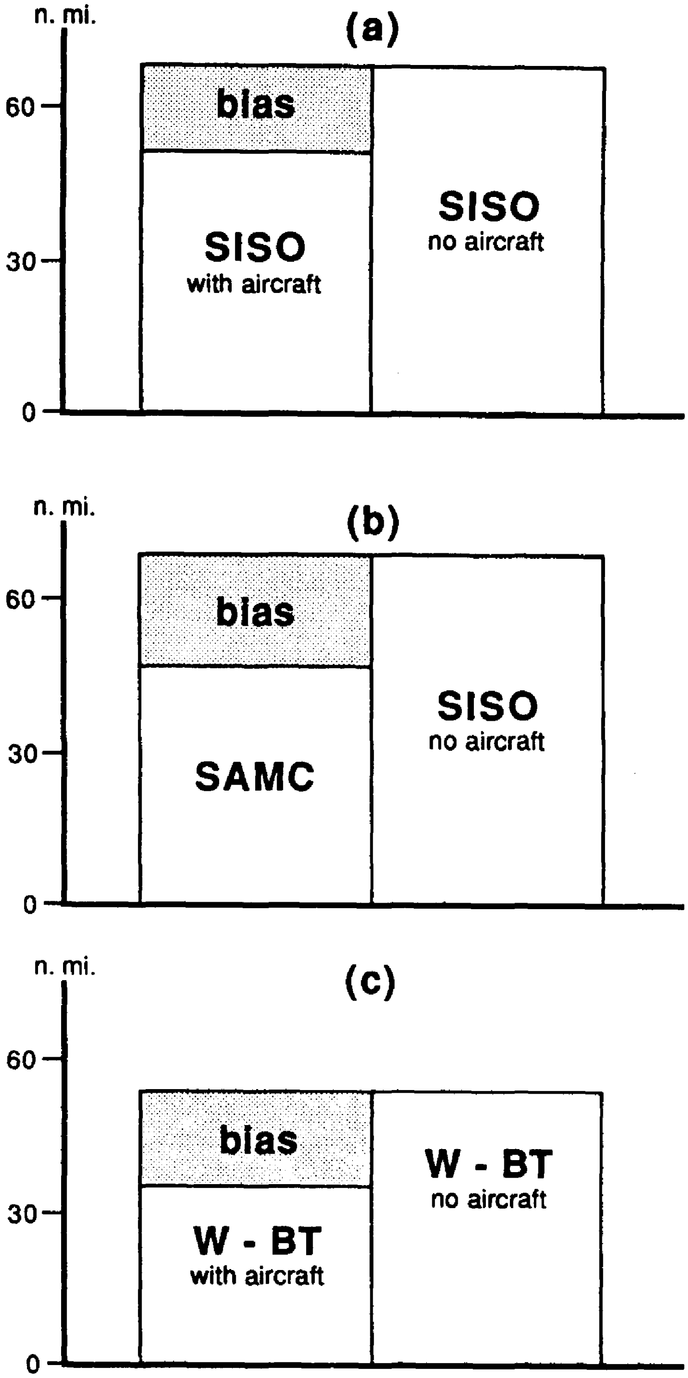


Figure 10.2: Same as Fig. 10.1 but for mean plus one standard deviation of positioning fix differences.

These results indicate that aircraft positioning influences on satellite fixes are nearly the same in both the SISO and SAMC data sets—producing reductions of about 25-30 percent. Note how W-BT positioning differences are generally smaller than are SAMC and SISO differences. Warning and best track determinations are being made with both aircraft and satellite information. This reduces positioning differences. These positioning differences appear to be a combination of:

1. lack of precision of the center fixing ability of the satellite due to inability to meteorologically locate the center
2. satellite gridding navigation problems,
3. small scale oscillatory motion of the TC center which induces center position differences in the smoothed analysis.

10.2 Aircraft influence on TC intensity estimates

As previously discussed in Chapter 6, TC intensity differences from the SAMC comparative data were much larger than from the SISO comparative information. Intensity comparisons of SAMC with aircraft information to SISO with and without aircraft information in the previous 12 hours are shown in Figs. 10.3a (mean) and 10.3b (mean plus one standard deviation). Note that despite having aircraft, two independent satellite observers were closer in their intensity determinations than satellite and aircraft observers. With or without aircraft information, SISO intensity estimates are much closer than those of satellite vs. aircraft SAMC measurements. As previously discussed, independent satellite observers are closer together in their intensity estimates when direct aircraft measurements are not available to complicate their intensity estimate. Satellite analysts are surprisingly consistent in their TC intensity estimations but not necessarily in their intensity estimates. This bias in satellite intensity determination appears to be 50 percent or more. Forecasters should be aware that satellite intensity estimates may be noticeably inaccurate at certain times despite agreements in intensity estimate judgement between two or more independent satellite observers.

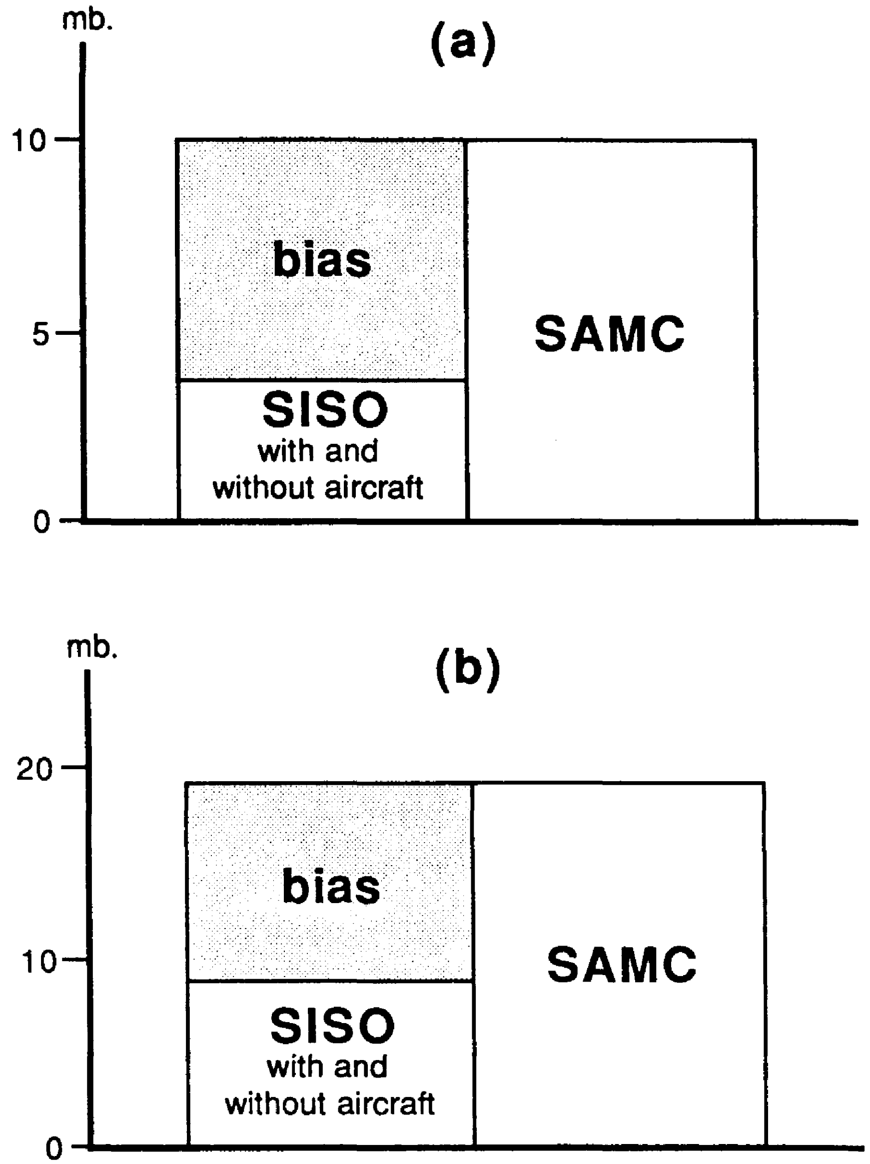


Figure 10.3: Comparison of SAMC and SISO (with and without aircraft) mean (a) and mean plus one standard deviation (b) intensity estimate differences.

Chapter 11

SUMMARY DISCUSSION

This study was undertaken to try to learn more about how accurately current satellite technology may be able to independently measure TC position, motion, and intensity and how such satellite measurement accuracies may influence 24- to 72-hour TC track predictions. This could only be indirectly inferred by studying the spread in independent satellite observations from each other and by study of the differences in biased satellite vs. aircraft measurements. We believe that this study's inferences on the impact of aircraft reconnaissance on TC analysis–forecasting is also valid for the Atlantic.

Sometimes the satellite does not accurately measure a TC's center position. The application of the Dvorak intensity techniques by operational personnel can sometimes lead to noticable intensity inaccuracies. Aircraft measurements would largely overcome both of these satellite position and intensity measurement deficiencies. By contrast, it appears that aircraft reconnaissance as it was previously employed in the NW Pacific did not, on average, appreciably improve the initial and conservative TC motion vector which is used in TC track model forecasts or of the average TC track forecasts beyond 24 hours.

This study indicates that one should expect a significant degradation in short range (< 24 hour) forecast skill through full reliance on the satellite without supplementary aircraft information. This is especially the case in the occasional badly satellite observed TC. Aircraft observations add confirmation to the satellite information and offer considerable assistance at the reduction of forecast error in some of the most difficult short range forecast situations. New weather satellite technology development in the next few years probably will not significantly change this assessment.

It should be stated again that this assessment of the impact of aircraft reconnaissance did not consider the question of whether the reconnaissance aircraft had been used to its highest potential for surrounding TC synoptic data gathering and better vortex core tracking, etc. These and other potential aircraft gains should likely be factored into consideration of the desirability of having aircraft reconnaissance. As aircraft instrumentation advances and as our general knowledge of how to more effectively utilize aircraft reconnaissance increases, it is likely that the general value of the aircraft for TC observing-forecasting will likely be found to be higher than it has in the recent past. Future technical advances in aircraft reconnaissance may be as large as the technical advances of the satellite.

Another area of consideration to aircraft reconnaissance is the ground–truth it provides for the testing of the current and new satellite observations. How can the present and new satellite sensors be tested for accuracy if verifying aircraft information is not available?

There is, of course, much more to be accomplished to better tie–down the influence of reconnaissance aircraft on satellite TC observation–forecasting. The next phase of this analysis will be to study individual cases of large satellite-observed TC position and/or intensity inaccuracy to try to better understand the specific meteorological and satellite observational difficulties which lead to these measurement shortcomings. It is the occasional large satellite fix and intensity inaccuracy which poses the largest warning threat. Such analysis in the NW Pacific must be accomplished during the period before 1987 when reconnaissance aircraft information was still available for ground–truth. We also hope to study how geostationary visual and enhanced IR image looping may be used in combination for improved eye determination and intensity change estimation.

There is also the question of the general scientific advance of our knowledge of TCs. Aircraft reconnaissance supplies important and unique TC observational information which the satellite cannot supply. It is to be expected that this added aircraft information will ultimately lead to a better basic understanding of the TC and to likely improvements in TC observation-forecasting.

There is also the curiosity component. Tropical cyclones have the potential to influence millions of people and to cause billions of dollars in property loss. They have become major media events in the US. The general public requests detailed information on TCs irrespective of the impact of such detailed information on the accuracy of the TC forecast or the TC's ultimate destructure. What would be the political implications resulting from a destructive TC which was not well forecast and for which reconnaissance aircraft flights were not made?

Whether aircraft reconnaissance is economically justified or not was not the concern of this study. All tropical cyclone forecasters and researchers would like to have aircraft reconnaissance. But we meteorologists are not faced with the task of establishing governmental and economic priorities. This is a much more complex issue. Valid economic judgments probably cannot be made, however, unless more technical studies of this type are first made to more objectively specify how well the satellite is able to observe the TC by itself without the supplementary support of the aircraft. Tropical cyclone aircraft reconnaissance may be economically justified in some TC basins but not in others.

For more background information on this subject the reader is referred to the supplementary reading list at the end of the cited references.

ACKNOWLEDGEMENTS

The author would like to thank Professor William M. Gray for his strong interest, encouragement, and overall support of this research endeavor. Members of Professor Gray's research group also provided assistance. In particular, William Thorson, who provided additional computer expertise necessary for the volumes of data which were processed, and Ray Zehr, who provided valuable expertise on the satellite capabilities for TC measurements, are thanked for their assistance. Ms. Barbara Brumit provided professional assistance in manuscript preparation.

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AUTOBIOGRAPHY

Captain (Major select) Joel D. Martin is in an Air Force Institute of Technology sponsored atmospheric science program (master's degree) at Colorado State University. He is a 1977 graduate of the University of Oklahoma with a bachelor of science in meteorology. Following graduation he was commissioned and entered the U.S. Air Force as a weather support forecast officer. His background includes over 700 flight hours as an aerial reconnaissance weather officer, including flights into Typhoon Owen (1979) and Hurricane Allen (1980). He also authored major software and statistical revisions to the aerial reconnaissance meteorological instrument calibration program in 1981. More recently, he was a regional director for officer recruiting and the chief business analyst for Headquarters Air Force Recruiting Service. He joined Professor W. M. Gray's tropical storm research project in August 1986.

DEDICATION

This thesis is dedicated to a few people who, in particular, have greatly influenced the author over the years.

- My late grandfather, D.B. Deeds, who gave me an early interest in meteorology and science.
- My late grandfather, James T. Martin, who showed that success in life is based on faith in God and hard work.
- My parents, Mr. and Mrs. Joe E. Martin, who fully supported my academic and military paths.
- My wife Elizabeth, a best friend and supporter through this academic endeavor.

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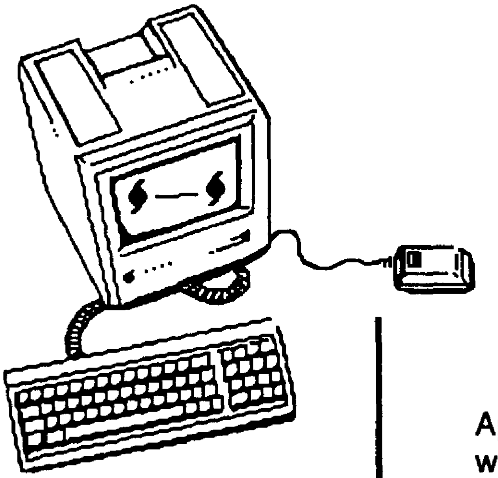
Appendix A

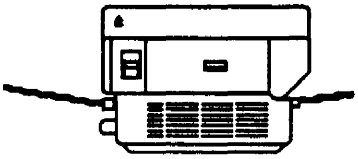
A REFERENCE TO THE PRINCIPLE COMPUTER HARDWARE AND SOFTWARE USED IN THIS STUDY

Guide to hardware and software used in this research



Computer Hardware

Apple Macintosh™ computer
with 2024K bytes RAM



Apple LaserWriter™ printer

Computer Software

Smartcom II

Hayes Smartcom II™ for data transfer from mainframe computer

QUED

Paragon Concepts Quality Editor for Developers (QUED)™ for data editing

StatView512+

StatView 512+™ by BrainPower for statisitcal analysis and graphics

SuperPaint

SuperPaint™ by Silicon Beach Software for graphics and design

ReadySetGo4

Ready, Set, Go! 4™ by Letraset for page layout and desktop publishing

Appendix B

GROUPING OF BASIC DATA SETS AND THE SUBSET VARIABLES CONTAINED IN EACH ANALYSIS CLASS

Common Data Set Variables

TC NAME
TC NBR
DATE/TIME
SUN
INT
PCT
CLO
SAT CI
IMG
SAT NAME

SAMC Positioning Variables

SAT LAT
SAT LON
AIR LAT
AIR LON
LAT DIFF
LON DIFF
DIST

SAMC Motion Variables

SAT U
SAT V
AIR U
AIR V
U DIFF
V DIFF
SAT SPD
AIR SPD
SPD DIFF

SAMC Intensity Variables

AIR CI
SAT SLP
AIR SLP
SLP DIFF
SAT SFC WND
AIR SFC WND
AIR FLT WND
WND DIFF 1
WND DIFF 2
WND DIFF 3

SISO Variables

NBR
LAT DIFF
LON DIFF
DIST
CI MAX
CI MIN
SLP DIFF
WND DIFF

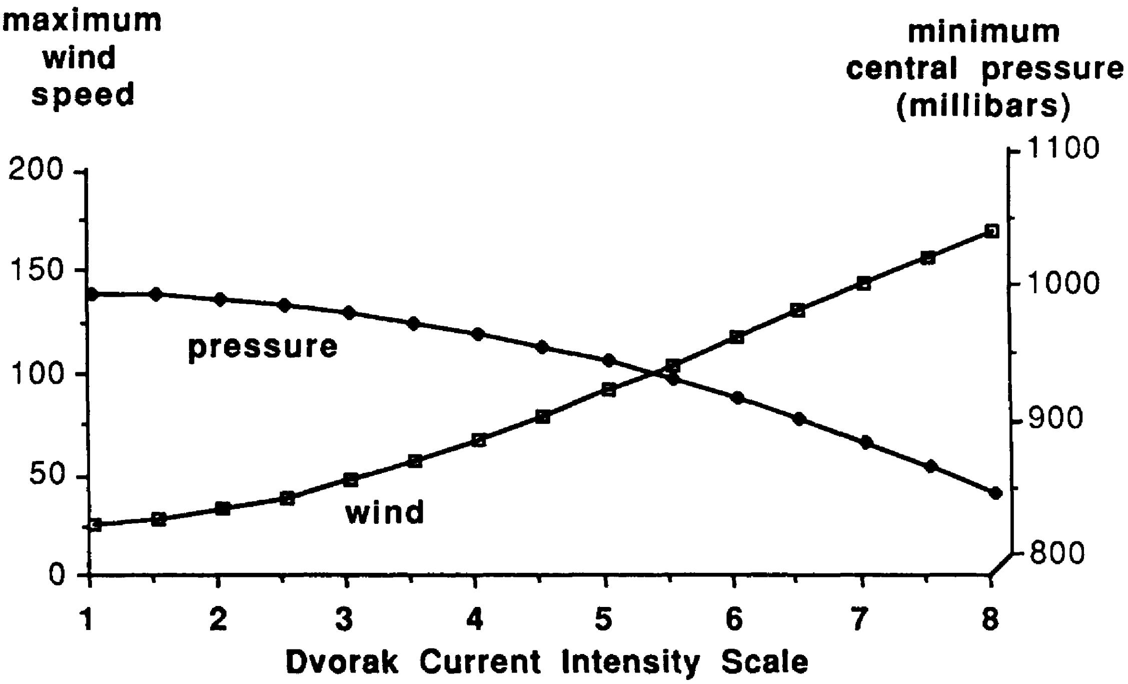
AIF Variables

CLS
TRK
PABT WND
WRG WND
PABT LAT
PABT LON
00 DIFF
24 DIFF
48 DIFF
72 DIFF
12 INT
6 INT

Appendix C

TC MAXIMUM WIND AND CENTRAL PRESSURE MAY BE ESTIMATED FROM THE CURRENT INTENSITY NUMBER AS SHOWN IN THE TABLE AND CORRESPONDING GRAPH (AFTER DVORAK, 1984)

CI number	MWS (knots)	MSLP (Atlantic)	MSLP (Pacific)
1.0	25		
1.5	25		
2.0	30	1009	1000
2.5	35	1005	997
3.0	45	1000	991
3.5	55	994	984
4.0	65	987	976
4.5	77	979	966
5.0	90	970	954
5.5	102	960	941
6.0	115	948	927
6.5	127	935	914
7.0	140	921	898
7.5	155	906	879
8.0	170	890	858



Appendix D

W. M. GRAY'S FEDERALLY SUPPORTED RESEARCH PROJECT REPORTS SINCE 1967

CSU Dept. of Atmos. Sci. Report No.	Report Title, Author, Date, Agency Support
104	The Mutual Variation of Wind, Shear and Baroclinicity in the Cumulus Convective Atmosphere of the Hurricane (69 pp.). W. M. Gray. February 1967. NSF Support.
114	Global View of the Origin of Tropical Disturbances and Storms (105 pp.). W. M. Gray. October 1967. NSF Support.
116	A Statistical Study of the Frictional Wind Veering in the Planetary Boundary Layer (57 pp.). B. Mendenhall. December 1967. NSF and ESSA Support.
124	Investigation of the Importance of Cumulus Convection and ventilation in Early Tropical Storm Development (88 pp.). R. Lopez. June 1968. ESSA Satellite Lab. Support.
Unnumbered	Role of Angular Momentum Transports in Tropical Storm Dissipation over Tropical Oceans (46 pp.). R. F. Wachtmann. December 1968. NSF and ESSA Support.
Unnumbered	Monthly Climatological Wind Fields Associated with Tropical Storm Genesis in the West Indies (34 pp.). J. W. Sartor. December 1968. NSF Support.
140	Characteristics of the Tornado Environment as Deduced from Proximity Soundings (55 pp.). T. G. Wills. June 1969. NOAA and NSF Support.
161	Statistical Analysis of Trade Wind Cloud Clusters in the Western North Pacific (80 pp.). K. Williams. June 1970. ESSA Satellite Lab. Support.
—	A Climatology of Tropical Cyclones and Disturbances of the Western Pacific with a Suggested Theory for Their Genesis/Maintenance (225 pp.). W. M. Gray. NAVWEARSCHFAC Tech. Paper No. 19-70. November 1970. (Available from US Navy, Monterey, CA). US Navy Support.

CSU Dept. of Atmos. Sci. Report No.	Report Title, Author, Date, Agency Support
179	A diagnostic Study of the Planetary Boundary Layer over the Oceans (95 pp.). W. M. Gray. February 1972. Navy and NSF Support.
182	The Structure and Dynamics of the Hurricane's Inner Core Area (105 pp.). D. J. Shea. April 1972. NOAA and NSF Support.
188	Cumulus Convection and Larger-scale Circulations, Part I: A Parametric Model of Cumulus Convection (100 pp.). R. E. Lopez. June 1972. NSF Support.
189	Cumulus Convection and Larger-scale Circulations, Part II: Cumulus and Meso-scale Interactions (63 pp.). R. E. Lopez. June 1972. NSF Support.
190	Cumulus Convection and Larger-scale Circulations, Part III: Broadscale and Meso-scale Considerations (80 pp.). W. M. Gray. July 1972. NOAA-NESS Support.
195	Characteristics of Carbon Black Dust as a Tropospheric Heat Source for Weather Modification (55 pp.). W. M. Frank. January 1973. NSF Support.
196	Feasibility of Beneficial Hurricane Modification by Carbon Black Seeding (130 pp.). W. M. Gray. April 1973. NOAA Support.
199	Variability of Planetary Boundary Layer Winds (157 pp.). L. R. Hoxit. May 1973. NSF Support.
200	Hurricane Spawned Tornadoes (57 pp.). D. J. Novlan. May 1973. NOAA and NSF Support.
212	A Study of Tornado Proximity Data and an Observationally Derived Model of Tornado Genesis (101 pp.). R. Maddox. November 1973. NOAA Support.
219	Analysis of Satellite Observed Tropical Cloud Clusters (91 pp.). E. Ruprecht and W. M. Gray. May 1974. NOAA/NESS Support.
224	Precipitation Characteristics in the Northeast Brazil Dry Region (56 pp.). R. P. L. Ramos. May 1974. NSF Support.
225	Weather Modification through Carbon Dust Absorption of Solar Energy (190 pp.). W. M. Gray, W. M. Frank, M. L. Corrin, and C. A. Stokes. July 1974.
234	Tropical Cyclone Genesis (121 pp.). W. M. Gray. March 1975. NSF Support.

CSU Dept. of Atmos. Sci. Report No.	Report Title, Author, Date, Agency Support
—	Tropical Cyclone Genesis in the Western North Pacific (66 pp.). W. M. Gray. March 1975. US Navy Environmental Prediction Research Facility Report. Tech. Paper No. 16-75. (Available from the US Navy, Monterey, CA). Navy Support.
241	Tropical Cyclone Motion and Surrounding Parameter Relationships (105 pp.). J. E. George. December 1975. NOAA Support.
243	Diurnal Variation of Oceanic Deep Cumulus Convection. Paper I: Observational Evidence, Paper II: Physical Hypothesis (106 pp.). R. W. Jacobson, Jr. and W. M. Gray. February 1976. NOAA-NESS Support.
257	Data Summary of NOAA's Hurricanes Inner-Core Radial Leg Flight Penetrations 1957-1967, and 1969 (245 pp.). W. M. Gray and D. J. Shea. October 1976. NSF and NOAA Support.
258	The Structure and Energetics of the Tropical Cyclone (180 pp.). W. M. Frank. October 1976. NOAA-NHEML, NOAA-NESS and NSF Support.
259	Typhoon Genesis and Pre-typhoon Cloud Clusters (79 pp.). R. M. Zehr. November 1976. NSF Support.
Unnumbered	Severe Thunderstorm Wind Gusts (81 pp.). G. W. Walters. December 1976. NSF Support.
262	Diurnal Variation of the Tropospheric Energy Budget (141 pp.). G. S. Foltz. November 1976. NSF Support.
274	Comparison of Developing and Non-developing Tropical Disturbances (81 pp.). S. L. Erickson. July 1977. US Army Support.
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297	Diagnostic Analyses of the GATE A/B-scale Area at Individual Time Periods (102 pp.). W. M. Frank. November 1978. NSF Support.
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TROPICAL CYCLONE OBSERVATION AND FORECASTING WITH AND WITHOUT AIRCRAFT RECONNAISSANCE

Colorado State University
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Subject Headings
Aircraft Reconnaissance
Tropical cyclones
Observation
Forecasting

USAF, ONR, NOAA/NWS

This study attempts to better quantify the contribution of aircraft reconnaissance to the accuracy of Tropical Cyclone center fix, motion determination, and intensity estimates along with the impact on track forecasts. What is the impact on TC observations and forecasts when forecasters must rely only on weather satellites?

Analyses concentrate on differences in TC position-intensity and track forecasting which occur between periods when aircraft measurements were taken vs. periods when measurements were not made. Study is made of data from the Northwest Pacific for the period 1979-86. Over 200 TC cases with about 5,000 center position fixes are analyzed. Average and distributions of fix, motion, intensity, and forecast error differences between reconnaissance and non-reconnaissance periods are made. Differences also are examined with respect to satellite type and day-night measurements. Positioning and intensity estimate differences from simultaneous independent satellite measurements are studied as well.

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