NOAA Technical Memorandum NWS SR-82

A STATISTICAL STUDY OF TROPICAL CYCLONE POSITIONING ERRORS WITH ECONOMIC APPLICATIONS

Charles J. Neumann
NHC, Miami, Florida

Scientific Services Division
Southern Region
Fort Worth, Texas
March, 1975

UNITED STATES DEPARTMENT OF COMMERCE
Frederick B. Dent, Secretary

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
Robert M. White, Administrator

National Weather Service
George P. Cressman, Director

A STATISTICAL STUDY OF TROPICAL CYCLONE POSITIONING ERRORS[1] WITH ECONOMIC APPLICATIONS

ABSTRACT

Hurricane landfall forecasts are based heavily on the latest available motion vector and position of a storm. Inaccuracies in these data are closely related to errors in the time and place of storm landfall. This study uses a Monte Carlo simulation of hurricane positioning errors to determine a statistical relationship between positioning errors and landfall errors. It is shown that for a typical 18-hour landfall forecast, approximately 22 percent of the landfall position error can be attributed to initial data uncertainties. It is further shown that a 20 percent increase in the size of a hurricane warning zone can be expected if the currently observed positioning errors are increased an average of 10 nmi. However, a 10 nmi decrease in positioning error yields only an 11 percent decrease in the size of the warning area.

The study continues with an economic analysis of potential changes in the size of hurricane warning areas. It is estimated that protection costs (including losses due to temporary curtailed production) for a typical 300 nmi Gulf of Mexico coastal hurricane warning zone total 25.1 million dollars. A 10 nmi increase in positioning error will thus increase this economic loss by about 5 million dollars per storm. A 10 nmi decrease in positioning error will decrease protection costs by about 2.75 million dollars per storm.

I. INTRODUCTION AND PURPOSE

The issuance of hurricane warnings along a portion of the United States coastline is generally accomplished 18 to 24 hours prior to expected arrival of a storm at the coast. This particular time interval has been found to be an optimized trade-off between the desire to provide maximum warning lead time and the ability to keep the size of the warning area within reasonable limits. With such a lead time, the length of the warning zone averages near 300 nmi. Sugg (1967) points out that inasmuch as the swath of damaging winds is generally less than 100 nmi, the public must expect a minimum overwarning area of about 200 nmi.

---

[1]A positioning error is defined as the difference between the forecaster's assumed initial position of a storm and the actual position as determined from a post-analysis.

Reduction in the average size of the overwarning area or increases in warning lead time can only be accomplished by improvements in the "state-of-the-art" of tropical cyclone forecasting. As pointed out by Neumann (1975), an important consideration in this regard is the role that persistence plays in tropical cyclone forecasting. For forecast periods of 24-hours or less, the latest motion vector (persistence) is the most important single factor contributing to the reduction of variance realized by most statistical tropical cyclone prediction models. With any forecast situation, uncertainties in the position and motion of a storm at the time a forecast is to be made often compromise this variance-reducing potential and contribute directly to increases in the errors associated with the prediction of the time and place of a hurricane landfall.

This paper concerns itself with several aspects of the initial data uncertainties. In Section 2 a statistical analysis is made of the observed positioning errors. In Section 3, the statistical distribution of positioning errors is used as the basis of a Monte Carlo simulation of hurricane landfall forecast situations. The simulation experiment leads to a specific statistical relationship between positioning error and landfall error.[2] The economic aspect of potential changes in the average size of hurricane warning areas is the subject of Section 4. A discussion of the results and a summary follows in Section 5.

The topic is somewhat similar to that discussed by Anderson and Burnham (1973) who speculated on potential economic benefits resulting from a decrease in the size of a warning area due to general improvements in tropical cyclone forecasting. In the current study, however, the emphasis is on the role that positioning errors play in potential changes (that is, either increases or decreases) in the size of hurricane warning areas. No attempt was made to evaluate economic losses from tropical cyclones below hurricane strength.

Discussions on procedural changes which could conceivably bring about changes in the current ability to specify a center of a tropical cyclone are beyond the scope of this paper. The purpose is merely to speculate on the results of such changes, however they may come about.

2. OBSERVED POSITIONING ERRORS IN THE ATLANTIC

In an operational environment, it is impossible to determine storm position and storm motion with the same precision as that implied by the best track.[3] It is beyond the scope of this paper to consider all the

[2]Landfall error is defined as the distance, measured along the coastline, between the forecast point of landfall and the observed point of landfall.

[3]Best track is defined as the accepted track of a storm after a thorough post-analysis.

possible reasons for this circumstance. The situation is perhaps best summed up by Hope (1971) who states that in arriving at a synoptic-time position the forecaster simply utilizes the latest and what he considers the most reliable information available at that time.

A post-analysis generally indicates that the forecaster's original estimate of storm position and hence, storm motion was somewhat in error. A summary of positioning errors in the Atlantic over the seven year period, 1968 through 1974, discloses that the average error is about 25 nmi.[4] If the area is confined to within 500 nmi of the United States, the average error is found to be near 22 nmi. The decrease is attributable to increased aircraft and radar surveillance as well as more positive gridding of satellite photographs when storms are close to the United States mainland.

The vector distribution of this latter group of errors is shown in Fig. 1. The origin represents the best-track position of the storm. Each of the points on the figure represent the end point of a vector drawn from the best-track position (origin) to the operational storm position.

For Monte Carlo simulation experiments it is convenient to identify a parent probability distribution. Accordingly, the array of error components on Fig. 1 was fitted to a bivariate normal distribution. It is obvious (and somewhat surprising) that this theoretical distribution does not adequately describe the observed density distribution. There are far too many observed cases near the centroid of the data sample than would be expected from the theoretical distribution. For example, the 0.25 elliptical envelope should contain approximately one-fourth (103) of the cases whereas it actually contains 216 cases. The 0.50 to 0.75 elliptical areas should also contain one-fourth the cases but actually contains 47 cases. Accordingly, if one were to select at random from the distribution rather than from the actual sample data, the mean absolute error would be overestimated. A test on 1000 random selections from the distribution indicates that the overestimation of mean absolute error is about 26 percent.

---

[4] In Neumann (1975), the average error for the five year period 1968-1972 was found to be near 27 nmi. The decrease suggests improved positioning accuracy in recent years.

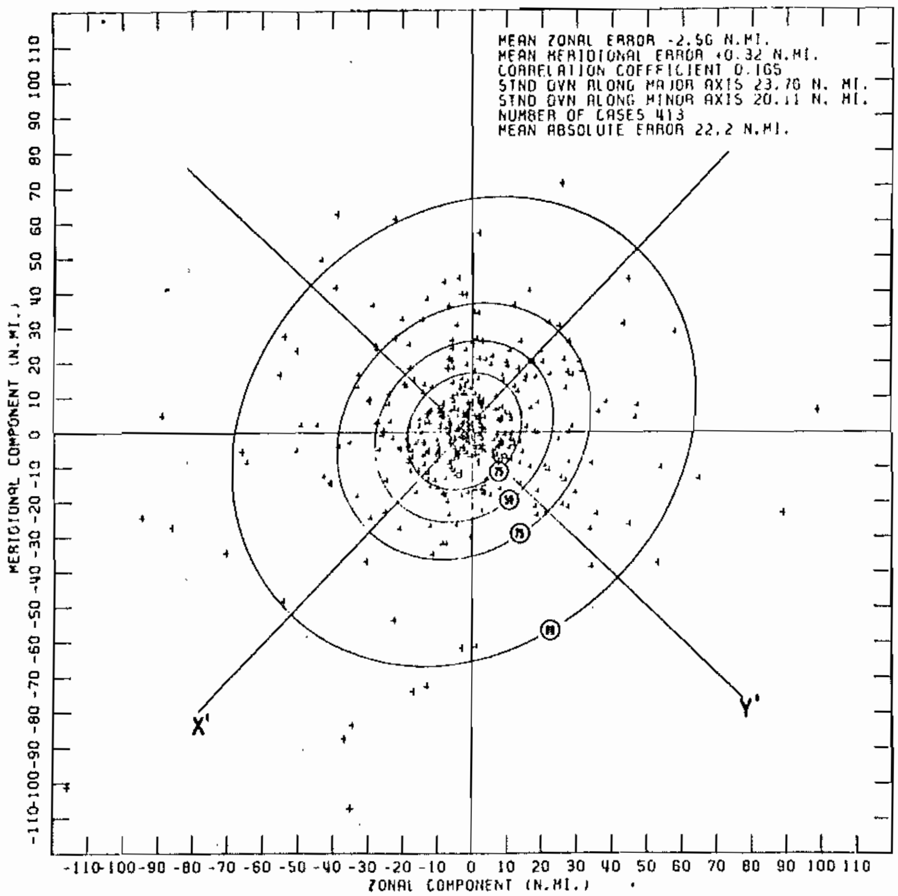

Fig. 1. Distribution of positioning errors for storms located within 500 nmi of the United States mainland. Origin represents position of storms determined from the best-track. The head of a vector drawn from origin to the operational storm position is shown by (+). Period of record 1968 through 1974. X'Y' coordinate system gives centroid of data as fitted to bivariate normal distribution.

3. SIMULATED LANDFALL FORECASTS

a. Choice of an objective forecast model - Before proceeding with the simulation experiment, it was necessary to select an objective prediction model which met certain requirements. Since a Monte Carlo simulation could potentially generate thousands of forecasts, the model could not use more than a few seconds of computer time for each forecast. Secondly, since the purpose of the experiment was to study the effects of uncertainties in storm positions, the model had to make explicit use of this parameter in the prediction algorithm. Thirdly, it was desirous, although not absolutely mandatory, that the model not require fields of upper-air synoptic data. Such data are not available prior to 1945 and it was necessary to use storms prior to this date to obtain a large enough control sample. These restrictions eliminated all but the HURRAN (Hope and Naumann, 1970) analog model and the CLIPER statistical model (Neumann, 1972). The latter was chosen in preference to the former due to its greater computer economy and convenience.

Certain modifications were made to the CLIPER forecast equations to make them compatible with the rationale behind the landfall simulation forecasts. The revised set of prediction equations requires the specification of the eight predictors listed in Table 1. Predictors P(9)

SYMBOL	PREDICTOR
P(1)	Current latitude.
P(2)	Current longitude.
P(3)	Zonal displacement zero to -12 hours.
P(4)	Meridional displacement zero to -12 hours.
P(5)	Zonal displacement -12 to -24 hours.
P(6)	Meridional displacement -12 to -24 hours.
P(7)	Julian day number.
P(8)	Maximum wind speed.

Table 1. Identification of the eight basic predictors required by the modified CLIPER prediction equations.

through P(44) are internally generated by the program. These additional predictors consist of all possible second-order products and cross-products of the eight basic predictors given in Table 1. The prediction equation for forecast zonal displacement (DX) for some given forecast interval is given by:

$$DX = C_0 + \sum_{i=1}^{44} C_i P_i \qquad (1)$$

where C_0 is the intercept and the remaining constants C_1 through C_{44} are determined by standard least squares methods. Similar rationale applies to the meridional motion prediction equations. Reasons for the use of a least-squares fit rather than a step-wise screening regression approach are discussed in Neumann and Randrianarison (1974).

An additional modification of the CLIPER equations involved the elimination of a forecast bias. The modified set of prediction equations was derived using dependent data for the entire Atlantic area, including the Gulf of Mexico. As will be pointed out in the subsequent subsection 3b, the simulation experiment was conducted only on Gulf of Mexico storms. Using the modified CLIPER equations in the Gulf of Mexico results in a slight bias to the right since storms in this area tend to have more northerly component than storms in the Atlantic located at similar latitudes. This slight bias was removed from the prediction equations prior to using this model exclusively on Gulf storms.

b. The control storms - In order to inject a degree of reality into the forecasts, only those hurricanes which had actually made landfall in the United States were considered as possible candidates for control storms. A number of reasons, most relating to convenience, led to the selection of the 25 hurricanes which had affected the New Orleans area between the years 1886 and 1974 as an acceptable set of storms. These storms are identified in Table 2, and their tracks are plotted in Figure 2. This set of control storms was used in two ways. Initially, simulated forecasts were prepared using best-track initial position and motion. Secondly, additional forecasts were prepared using simulated operational position and motion errors.

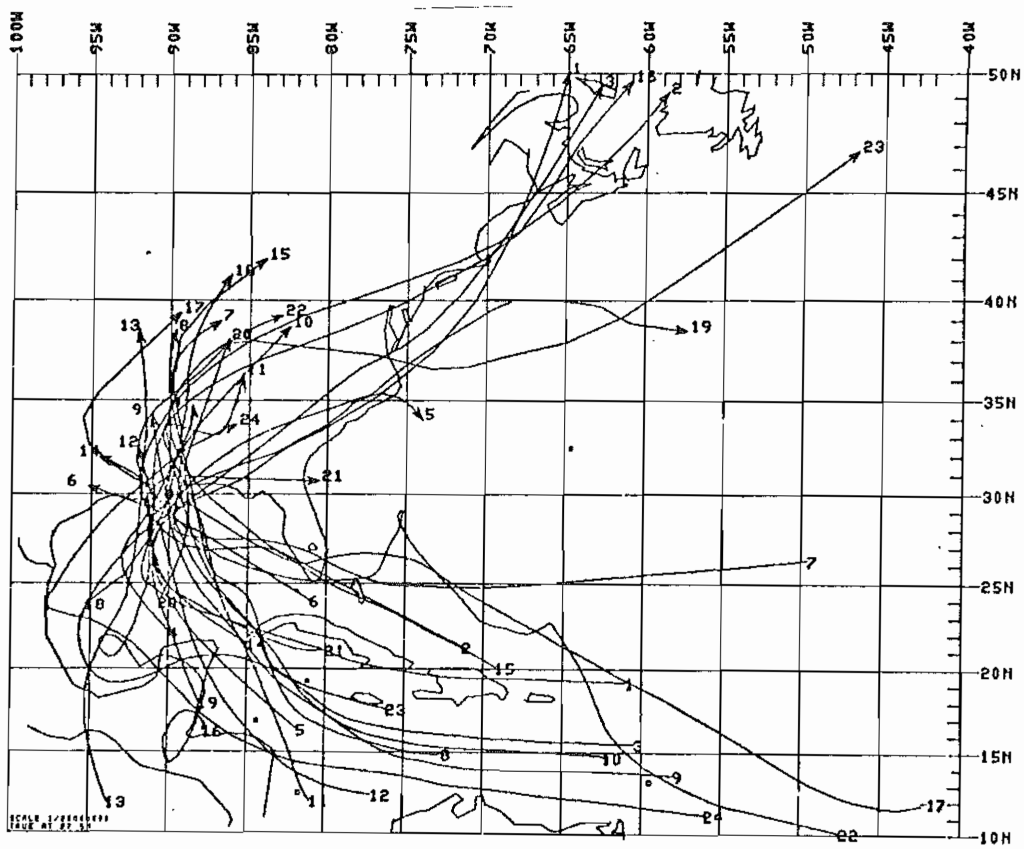

Fig. 2. Tracks of the 25 "control" storms. Storm numbers are identified in Table 3.

Cumulative Storm Number	Year	Landfall Date (EST)	Landfall Long. At 30 N	Storm Name
1	1887	Oct 19	89.5 W	---
2	1888	Aug 19	92.1	---
3	1889	Sep 23	88.2	---
4	1893	Sep 08	90.7	---
5	1893	Oct 02	89.2	---
6	1897	Sep 12	93.2	---
7	1901	Aug 15	89.5	---
8	1906	Sep 27	88.5	---
9	1909	Sep 20	90.2	---
10	1915	Sep 29	90.2	---
11	1916	Jul 05	88.7	---
12	1920	Sep 21	91.1	---
13	1923	Oct 16	91.4	---
14	1926	Aug 26	91.4	---
15	1932	Sep 01	87.6	---
16	1934	Jun 16	91.0	---
17	1947	Sep 19	89.7	---
18	1948	Sep 04	90.0	---
19	1956	Sep 24	87.4	Flossy
20	1960	Sep 15	91.5	Ethel
21	1964	Oct 04	91.4	Hilda
22	1965	Sep 10	91.1	Betsy
23	1969	Aug 17	89.3	Camille
24	1971	Sep 16	92.3	Edith
25	1974	Sep 08	92.1	Carmen

Table 2. The 25 storms selected as "control storms". Column labeled cumulative storm number refers to numbers appearing on Fig. 2. Dashes indicate storm not formally named.

c. Best-track forecasts on control storms - The coast along the northern Gulf of Mexico is conveniently simulated by the thirtieth parallel. Accordingly, the longitude where each storm crossed 30N was recorded (see Table 2). Also recorded were the locations of these storms at six-hourly intervals from 12 to 36 hours prior to making landfall at 30N. A quadratic interpolation scheme given by Akima (1970) was used to determine these positions. For each of the forecast periods, the necessary input parameters to the CLIPER model (see Table 1) were determined from the observed storm tracks. Simulated forecasts, one for each of the time periods 12 to 36 hours prior to landfall, were prepared on each of the 25 storms. A summary of the resultant landfall errors is given in Table 3. For reasons discussed in subsection 3a, the bias (mean algebraic error) of the storm sample landfall was near zero and was not included in Table 3.

Forecast Interval	Mean Absolute Error	Standard Error
12 hours	24	33
18 hours	52	69
24 hours	79	107
30 hours	105	139
36 hours	114	143

Table 3. Landfall errors (nmi) on sample of 25 control storms using best-track initialization data.

d. Simulated operational forecasts on control storms - The 12-, 18-, 24-, 30-, and 36-hour forecasts on the set of 25 control storms were repeated with predictors P(1) through P(6) of Table 1, modified so as to simulate operational conditions. This modification was accomplished by the inclusion of position errors randomly selected from the distribution shown in Figure 1. For the initial position, the full amount of the error component was used. For the -12 hour position, one-half of the error was used while for the -24 hour position, one-fourth of the error component was used. Predictors P(1) through P(6) were obtained from these modified positions. Such a procedure closely parallels operational conditions where the current position of a storm is the least certain and the -24-hour position specified by the forecaster is apt to be close to the later determined best-track.

One hundred simulated forecasts were made on each of the 25 control storms for each of the five forecast time periods, 12 through 36 hours, giving a total of 12,500 forecasts. A summary of these results is given in Table 4. Comparison with the data given in Table 3 shows an expected increase in both the mean absolute error and the standard error. Of particular interest is the amount of landfall error which can be attributed solely to the observed positioning error. For any given landfall forecast period, an error ratio (R) can be defined as:

$$R = (E_{op} - E_{bt})/E_{op} = 1.0 - E_{bt}/E_{op},$$

where E_{op} is the landfall mean absolute error from operational data and E_{bt} is the mean absolute error from best-track data. A graph of the quantity R vs. landfall forecast interval is given in Fig. 3. Thus, for the typical 18-hour landfall forecast, approximately 22 percent of the landfall error can be attributed exclusively to positioning (and initial motion) errors.

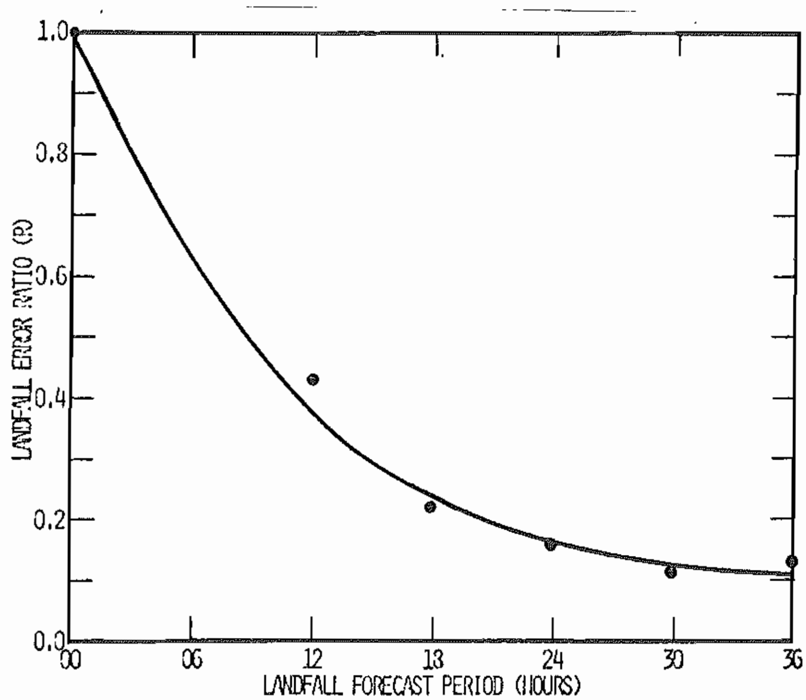

Fig. 3. Statistical relationship between landfall forecast period and the proportion of landfall error which can be attributed to positioning errors (landfall error ratio). Curve subjectively fitted to the six data points.

Forecast Interval	Mean Absolute Error	Standard Error
12 hours	42	55
18 hours	67	86
24 hours	94	125
30 hours	118	158
36 hours	131	171

Table 4. Landfall errors (nmi) on sample of 25 control storms using simulated operational initialization data.

e. Additional simulated landfall forecasts - In order to determine the effects of possible decreases or increases in positioning errors, the procedures described in the preceding subsection 3d were repeated using error distributions 25, 50, 75, 125, 150, and 175 percent as great as the observed error distribution shown in Fig. 1. With the larger position errors, there were occasions when the storm failed to reach the coast in the 72-hour forecast period. In these cases, the landfall error was taken as the distance between the 72-hour forecast storm position and the observed landfall position.

These additional computer runs provide sufficient data to obtain a statistical relationship between positioning error and the standard deviation of landfall error (standard error). As will be shown later, this relationship is needed if one is to determine potential changes in the size of a hurricane warning zone. The various computer simulation runs provided the data points shown on Fig. 4. The standard errors using best-track data (Table 3) are plotted vertically at a positioning error of zero. The remaining standard landfall errors, obtained by using the simulated positioning errors, are plotted vertically along the appropriate positioning error after allowing for the 26 percent bias (see Section 2) one obtains by using the distribution shown in Fig. 1.

The entire array of standard errors (S), positioning errors (P), and forecast time (T), were next fitted to a cubic regression surface.

$$S(P,T) = \sum_{\substack{i=0,3 \\ j=0,3}} \left(\prod Q_{ij} P^i \; T^j \right) \qquad i + j \leqslant 3 \qquad (2)$$

with the constants Q obtained according to the method described by Neumann and Hope (1972). The resulting algebraic equation contains 10 terms, each term of the form $Q_{ij}P^iT^j$. These are listed in Table 5. The multiple correlation coefficient of the fit is 0.99 indicating a nearly perfect relationship between the three variables S (standard landfall error), P (positioning error) and T (forecast time interval).

The solution of Eq. 2 over the range of T from 12 to 36 hours at 3-hourly intervals and the positioning error from zero to 45 nmi is shown in Fig. 4. It can be noted that the landfall errors increase very slowly beyond 33 hours and additional computer simulation runs at T beyond 36 hours show that the landfall standard errors tend to become constant at 42 hours. This is a consequence of the orientation of the coastline and would not be the case for landfall errors in general.

The 20 nmi mean positioning error cited on Fig. 4 is slightly less than that computed from the data plotted in Fig. 1. These latter data include all positioning errors on storms located within 500 nmi of the United States coastline. Since landfall forecasts are made from distances no more than 300 nmi, it was considered appropriate to make this small downward adjustment.

Q_{ij}		P^i		T^j
-0.87108	....	P^0	....	T^0
-0.1213283	....	P^0	....	T^1
+0.3296706	....	P^0	....	T^2
-0.0058799	....	P^0	....	T^3
-0.3523440	....	P^1	....	T^0
-0.0026132	....	P^1	....	T^1
+0.0003933	....	P^1	....	T^2
+0.0667732	....	P^2	....	T^0
-0.0001427	....	P^2	....	T^1
-0.0002667	....	P^3	....	T^0

Table 5. List of terms $Q_{ij}\ P^iT^j$ in Equation 2.

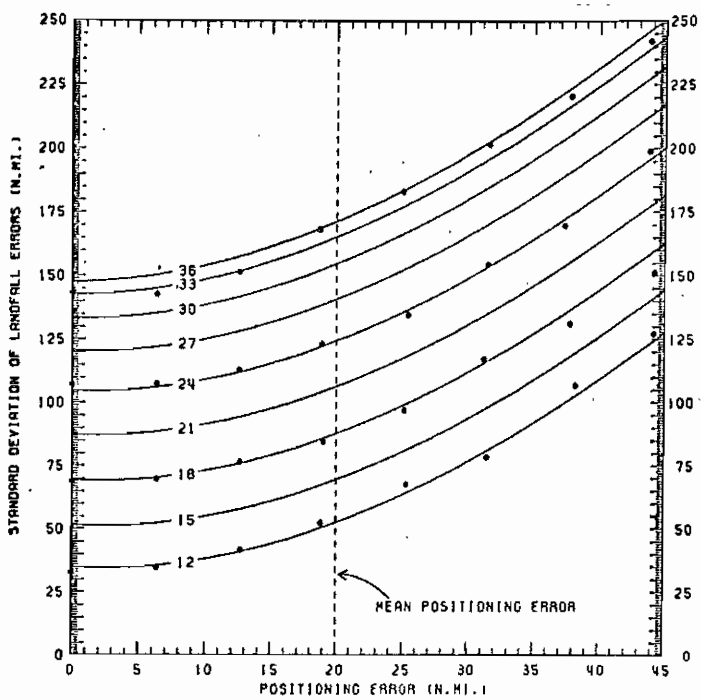

Fig. 4. Statistical relationship between positioning error and standard landfall error. Darkened circles show location of data points from computer simulation runs. Sloping lines represent cubic regression equation (2) fit to these data. Multiple correlation coefficient of fit is 0.99. Vertical dashed line shows the mean positioning error for storms located within 24-hours of landfall.

f. Calculations on the size of the warning area - The total width (W) of a coastal hurricane warning area consists of the forecast swath (H) of damaging winds plus an additional distance (Z_L) to the left and a distance (Z_R) to the right of the damage swath to account for uncertainties in the forecast. For a given hurricane forecast situation, the distance Z_L is not necessarily equal to Z_R. Each is determined by a number of subjective factors including the synoptic situation, the proximity of large population centers and the confidence the forecaster places in the projected track. Over a long period of time, however, Z_L can effectively be taken as equal to Z_R in which case,

$$W = H + 2Z \qquad (3)$$

where $Z = Z_L = Z_R$. A schematic warning zone is illustrated in Fig. 5. A study of landfall errors between the years 1970 and 1974 (Pelissier, 1974), the data given in Table 4 and data given by Sugg (1967) suggest

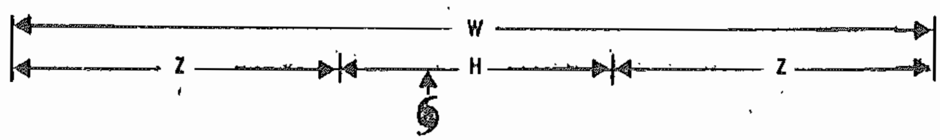

Fig. 5. Idealized hurricane warning zone.

that Z is about 1.5 to 2.0 times larger than the standard deviation of landfall errors. Assuming that the landfall errors are normally distributed, this means that, based on the original forecast, a storm can be expected to make landfall within the bounds of the forecast warning zone W approximately 85 to 95 percent of the time.

The distance Z can be effectively expressed as,

$$Z = NS(P,T) \qquad (4)$$

where N is the confidence factor (number of standard errors) which the forecaster effectively uses and S(P,T) is the standard error of the landfall forecast as given by Eq. 2. Eq. 3 then becomes,

$$W = H + 2NS(P,T). \qquad (5)$$

If H is taken as 75 nmi (typical of observed damage swaths), if N is taken as unity and if positioning error (P) is taken as 20 nmi, and if T is taken as 18 hours, then S(P,T) from Fig. 4 is read as 88 nmi and W, computed from Eq. 5, is found to be near 251 nmi. If the positioning error is increased to 30 nmi while the other variables are held constant, then W becomes 299 nmi, a near 20 percent increase over that observed using the average 20 nmi positioning error.

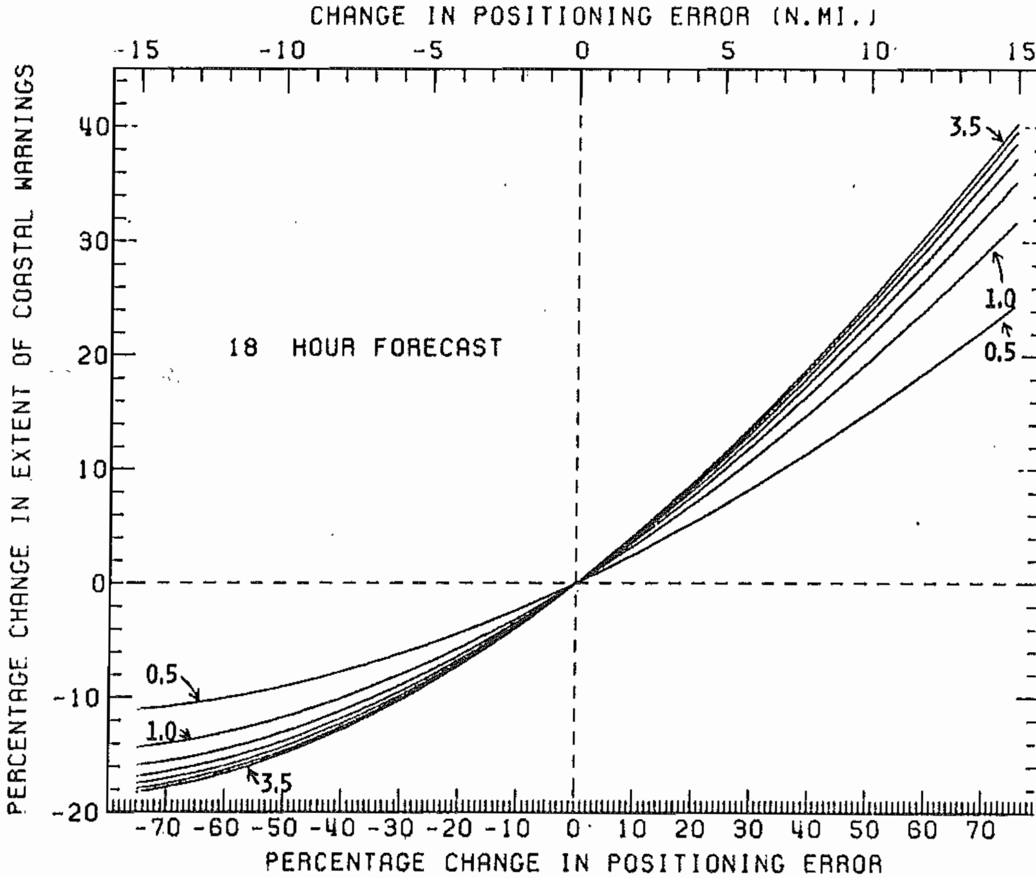

Fig. 6. Percentage changes in extent of coastal warnings to be expected with various positioning errors. Zero positioning error represents 20 nmi. Family of curves drawn for various confidence factors (number of standard errors) used in arriving at width of landfall forecast zone. Confidence factor is typically set at 1.5 to 2.0 standard errors. Forecast period is 18 hours.

With a fixed damage swath of 75 nmi, and with the quantities N and T assigned some given value, different selections of the positioning error P gives a range of percentage changes in the quantity W. Figs. 6 and 7 were prepared to show all of these possible ranges. For the case cited in the preceding paragraph, for example, ΔW is read from Fig. 6 as 19.8 percent.

Figs. 6 and 7 show that substantial changes in the size of coastal hurricane warning zones would result with any changes in the currently observed positioning errors. Because the slope of the curves increases from left to right, a given increase in positioning error increases the length of the coastal warning zone more than this same numerical decrease in the positioning error would decrease the size of the warning

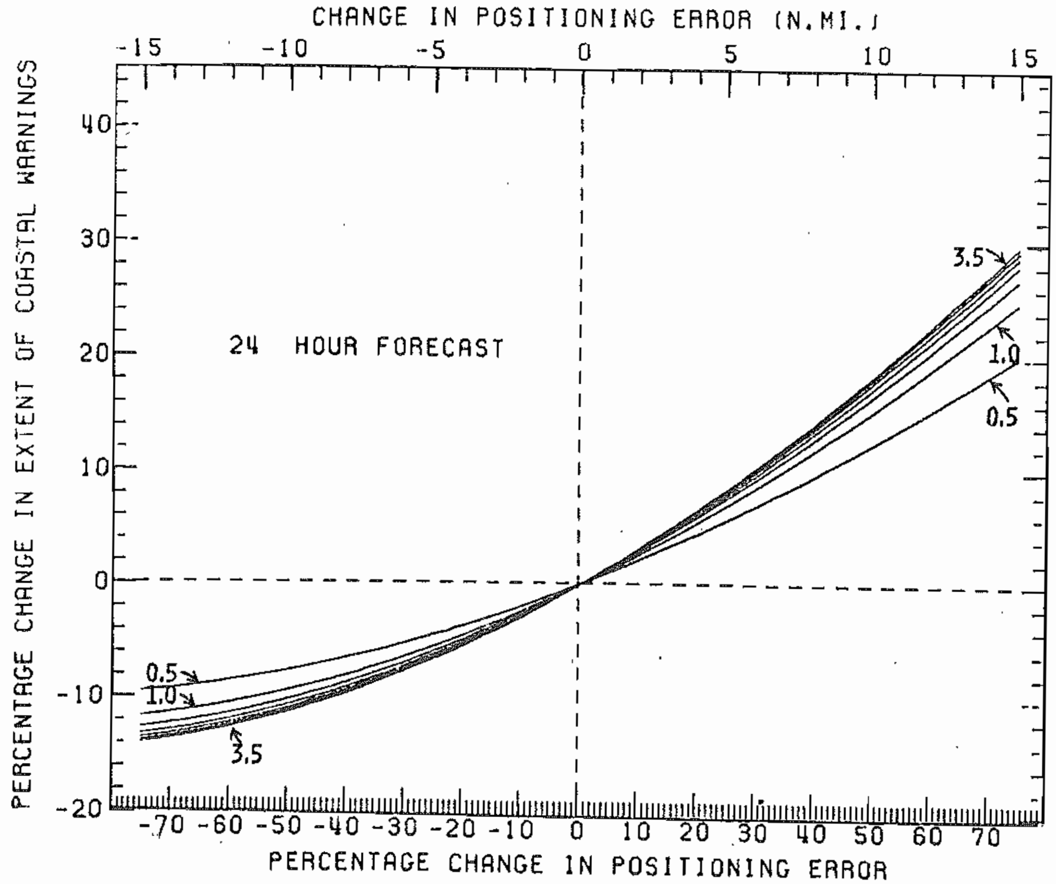

Fig. 7. Same as Fig. 6 except for 24 hours.

zone. In other words, there is a diminishing benefit ratio as positioning errors are possibly reduced below current values. Another significant feature of Figs. 6 and 7 is the larger percentage changes one can expect with the shorter-range landfall forecasts.

4. ECONOMIC ASPECTS OF CHANGES IN POSITIONING ERROR

As shown in Table 6, the average population per 300 nmi of U.S. Gulf coastline as of 1974 is about 1.75 million. A 20 percent increase in the size of an average warning area would thus affect approximately 350 thousand additional inhabitants plus a number of municipalities, coastal oil rigs, military installations, industrial complexes, etc. What does this mean in terms of actual increased preparedness costs? To answer this question, it is necessary to estimate the average protection costs per average size warning zone. While some of these costs such as those borne by military installations are easily determined; others,such as those borne by an average citizen or by the industrial segment, are quite subjective and require some simplifying assumptions if one is to arrive at a cost estimate. Reference to previous studies dealing with economic aspects of hurricane forecasting, notably Hawkins and Bilhorn (1971), Sugg (1967), Anderson and Burnham (1973), Brand and Blelloch (1974), led to the selection of five cost categories. Each of these will be discussed in turn.

Number of inhabitants GLFMEX coastal counties according to 1970 Census	6,958,401
Rate of increase per year (1960 to 1970)	2.2 percent
Estimate of number of inhabitants as of 1974	7,567,261
Length of coastline Brownsville to Key West	1300 nmi
Number of 300 nmi zones (1300/300)	4.33
Average population per 300 nmi zone	1,746,425

Table 6. Computation of average population per 300 nmi of Gulf of Mexico coastline. Population data summarized from Hebert and Taylor (1975).

a. Municipal and private costs - Economist Anderson and co-author Burnham (1973) recommend the use of $4.50 as the typical per capita cost for each hurricane protected against (i.e., $18 per family of four). The figure is based principally on a RAND study (Demsitz, 1962) and includes protection to private, commercial and city owned buildings as well as private and city labor time lost due to storm preparation. The figure does not include lost production and preparedness costs of large industrial plants.

Sugg (1967) presents information which suggests that only 20 percent of the population take any action upon receipt of hurricane warnings. However, inhabitants along the Gulf Coast are considerably more hurricane conscious since Camille of 1969. Accordingly this figure has been adjusted upward to 50 percent for the Gulf of Mexico coastal sections. The 1974 protection costs for this item are thus estimated to be $4.50 x cpi x 50 percent x 1,746,425 or $6,680,000. The term cpi refers to the Bureau of Labor Statistics consumer price index used to bring the costs up to the 1974 level.

b. Evacuees from coastal areas - The number of people who evacuate from coastal areas varies considerably from storm to storm. There were 350,000 (Dunn, 1962) out of 810,000 possible evacuees from Hurricane Carla of 1961; 300,000 (Sugg, 1966) of 2,206,000 possible evacuees from Hurricane Betsy of 1965; and 175,000 of 2,015,000 potential evacuees from Camille in 1969. These figures suggest that only about 15 percent of the population evacuates from a warning area. Most of these, of course, are from the immediate coastal zones which are subject to storm surge flooding. A recent evacuation study by Hans and Sell (1974) recommends using $12.00 per person per day for private housing and transportation evacuation costs and $5.55 per person per day for those preferring to use public housing and transportation. The authors further point out that only 20 to 25 percent of evacuees use the public facilities. This computes to an average cost of about $10.50 per person per day for evacuation. Multiplying this cost estimate by 15 percent of the average warning zone population gives a cost estimate of $5,501,239 per warning zone for this item for an average two day evacuation. Hans and Sell also recommend including additional costs because of the lost potential income of evacuees. However, this item was included under municipal and private costs.

c. Military costs - A study by Malone and Leimer (1971) presents hurricane damage protection costs for all U. S. military installations subject to Atlantic hurricane damage. An analysis of these data shows that within 300 nmi inland from the coast, there are approximately 8.3 military bases within an average 300 nmi hurricane warning area. The average cost per base is given as $197,000. Adjustment to the cpi gives a cost estimate for this item as $2,458,100.

d. Coastal and near offshore oil rigs - Tubb (1974) states that, "the number of mobile oil rigs is growing at an unbelievable pace". On a worldwide basis, the number of such rigs has increased from 1 in 1950 to 150 in 1966 (Howe, 1966) to 408 in 1974. Approximately 20 percent of these operate at any one time in the Gulf of Mexico. In addition, there are hundreds of manned and unmanned fixed drilling platforms. Wilson (1966) points out that Hurricane Inez which moved generally westward across the southern Gulf in 1966 cost the 10 major oil companies $1,500,000 for preparedness. The increase in the number of rigs and the cpi lead to a, perhaps, conservative estimate for this item as $2.5 million per storm.

e. Industrial costs - Perhaps the most intangible item in the economic aspects of this study is the protective action costs (including lost production) borne by the industrial segment of the population. According to the latest edition of the Houston, Gulf Coast Chemical Directory, there are well over 200 petrochemical companies located along coastal Texas and Louisiana. Blumberg (1974) estimates protective action losses to some of the larger companies as high as one million dollars a day, primarily from lost revenue. In an extensive study of potential economic benefits from improved forecasting along the Gulf coast, Hawkins and Bilhorn (1971) cite a particular industrial organization whose operating losses (equipment and production revenue) without taking protective action from one hurricane could be 65 million dollars but with adequate warning could be cut by 50 percent. With such a potential loss, the decision of least regret would generally be to take protection action even though such action may also require curtailed production.

Hawkins and Bilhorn further cite numerous additional potential economic benefits which could be realized by the industrial segment given better weather forecasts in general. Without extensive further study it is difficult to single out hurricane related costs from non-hurricane related costs. However, considering the information available, the preparation costs for a typical 300 nmi hurricane warning zone are, perhaps, conservatively placed at 8 million dollars. This dollar figure is considerably higher than the comparable "special interests" figure of 2 million given by Sugg (1967). However, considering dollar depreciation and increases in petroleum costs, the 8 million dollar estimate does not seem unreasonable.

f. Summary of protection cost estimates - Several authors cite additional indirect protection costs. Anderson and Burnham (1973), for example, point out that if a greater percentage of the population protects because of improved forecasting, over-protection costs due to hurricane warnings will increase. These secondary costs are difficult to evaluate and were not considered in the present study. A summary of the five cost items discussed in subsections 4a through 4e is given in Table 7.

1.	Municipal and private costs	$6,680,000
2.	Evacuation from coastal areas	5,501,239
3.	Military costs	2,458,100
4.	Costs for mobile and fixed oil drilling rigs	2,500,000
5.	Costs to large industry (includes production loss)	8,000,000
	Total cost	$25,139,339

Table 7. Estimate of protection costs for an average 300 nmi hurricane warning zone along the Gulf of Mexico coastline.

The estimate of 25.1 million dollars is somewhat similar to that effectively given by Anderson and Burnham. It is stressed, however, that the estimate was derived using a number of assumptions. Further in-depth economic research could conceivably alter the cost estimate by a considerable amount.

5. DISCUSSION

The total protection costs per 300 nmi of coastline per hurricane have been estimated as $25.1 million. According to both Cry (1965) and Simpson and Lawrence (1971), there are about 2 hurricanes which annually move inland across continental United States. Assuming that the protection costs for the U. S. Atlantic coast would approximate those along the Gulf coast, then the mean annual cost for hurricane damage protection along the coastal U.S. is about $50 million. This dollar estimate can be used in conjunction with Figs. 6 and 7 to estimate the added or decreased protection costs resulting from changes in positioning error. For example, Fig. 6 shows that a 10 nmi (50 percent) increase in positioning error would require a 20 percent larger warning zone if one is to maintain the same level of confidence in the landfall forecast. Accordingly, the additional costs would amount to 10 million dollars annually. It is interesting to note from Fig. 6 that a similar 50 percent decrease in positioning error would give only an 11 percent or 5.5 million cost savings annually. Thus, there appears to be a diminishing cost benefit ratio which can be realized from decreased positioning errors.

The question arises as to the validity of using the CLIPER forecast model as the basis of the Monte Carlo simulation experiment. Forecast verification data generally show that the landfall forecast error from official public forecasts are less than that obtained from the CLIPER (or any other) model. It is believed, however, that this would merely shift the family of curves on Fig. 4 downward and would not significantly alter the slope of the curves. It is the slope of the curves rather than the absolute ordinate value which determines the derived curves shown in Figs. 6 and 7. The CLIPER model as well as other statistical prediction models all rely heavily on persistence for the short-range forecasts. The same is true for the operational hurricane forecaster. The latest motion vector is the prime factor involved in determining the place of landfall. Errors in this vector will have similar detrimental effects on the official public landfall forecast as well as the objective techniques. The results obtained are thus believed to be relatively independent of forecast system.

If one compares Fig. 6 with Fig. 7, it can be noted that the shorter-range forecast yields greater percentage changes in the size of the coastal warning area. In actual practice, the lead-time of landfall forecasts is generally closer to 18 than it is to 24 hours. Accordingly, Fig. 6 should be used for cost estimates.

Stated concisely as possible, the significant results of this study are as follows:

1. For storms located within 500 nmi of the continental United States, the average positioning error is about 22 nmi. For storms within one day strike time (200 - 300 nmi) of the U.S. coast, the average positioning error is estimated to be near 20 nmi.

2. For the typical 18-hour landfall forecast, approximately 22 percent of the landfall error can be attributed to this average 20 nmi positioning error.

3. The extent of a coastal hurricane warning zone is such that a storm will fall within the area 85 to 95 percent of the time.

4. A 50 percent increase in currently observed positioning error would result in a 20 percent increase in the average length of a coastal warning zone while a 50 percent decrease would decrease the average length of the zone by about 11 percent.

5. The preparedness and lost production costs for a typical 300 nmi coastal hurricane warning zone along the Gulf of Mexico is estimated to be near 25.4 million dollars.

6. Using an average of 2 hurricanes a year to strike the U.S. mainland, a 50 percent increase in positioning error would result in an economic loss of 10 million dollars annually. A 50 percent decrease in positioning error translates into an economic gain of 5.5 million annually.

6. ACKNOWLEDGEMENTS

Section 4 of this study necessitated numerous telephone contacts with people knowledgeable in the economic aspect of hurricane warnings. Their assistance is appreciated. Information received from Mr. Randolph Blumberg, President, American Science and Engineering Company, Houston, Texas, and Mr. Samuel Brand of the U. S. Navy Environmental Prediction Research Facility, Monterey, California, was particularly helpful. Mr. Brian Jarvinen of the National Hurricane Center Research and Development Unit, provided considerable assistance in the literature search associated with economic aspects of the study.

REFERENCES

Akima, H., 1970: A new method of interpolation and smooth curve fitting based on local procedures. J. Assoc. Computing Mach., 17, 589-602.

Anderson, L.G. and J. M. Burnham, 1973: Application of economic analyses to hurricane warnings to residential and retail activities in the U.S. Gulf of Mexico coastal regions. Mon. Wea. Rev., 101, 126-131.

Blumberg, Randolph, President, American Science and Engineering Company, Houston, Texas, (Personal Communication) Nov. 1974.

Brand, S. and J. W. Blelloch, 1974: Cost effectiveness of typhoon forecast improvements, ENVPREDRSCHFAC Tech. Paper No. 8-74, Naval Postgraduate School, Monterey, Calif., 31 pp.

Cry, G.W., 1965: Tropical cyclones of the North Atlantic ocean. USWB Tech. Paper No. 55, 148 pp.

Demsetz, H., 1962: Economic gains from storm warnings. Memorandum RM-3168-NASA, The RAND Corporation, Santa Monica, Calif., 43 pp.

Dunn, G.E. and staff, 1962: The hurricane season of 1961. Mon. Wea. Rev., 90, 113.

Hans, J.M. and T.C. Sell, 1974: Economic risks - an evaluation. EPA-520/6-74-002 U.S. Environmental Protection Agency, Office of Radiation Program, Las Vegas, Nev.

Hawkins, T.E. and T.W. Bilhorn, 1971: A study of data buoy network for the Gulf of Mexico. NOAA Contract Report DOT-CG-03279-A, Gulf Universities Research Corp., Galveston, Texas.

Hebert, P.J. and J.G. Taylor, 1975: Hurricane experience levels of coastal counties from Texas to Maine. (Submitted to NWS, Southern Region Hdqs as Technical Memorandum)

Hope, J.R. and C.J. Neumann, 1970: An operational technique for relating the movement of existing tropical cyclones to past tracks. Mon. Wea. Rev., 98, 925-933.

Hope, J.R., 1971: Position error of tropical cyclones vs. frequency of aircraft fixes. J. Appl. Meteor., 10, 1035-1036.

Howe, R.J., 1966: Research. Hurricane Symposium, Amer. Soc. for Oceanography, Publication 1, 330, 340.

Malone, M.J. and D.R. Leimer, 1971: Estimation of the economic benefits to DOD from improved tropical cyclone forecasting. Headquarters Military Airlift Command, Scott AFB, Ill., 25 pp. plus appendix.

Neumann, C.J., 1972: An alternate to the HURRAN tropical cyclone forecast system. NOAA Tech. Memo. NWS SR-62, 32 pp.

Neumann, C.J. and E.A. Randrianarison, 1974: Statistical prediction of tropical cyclone motion over the Southwest Indian Ocean. (Submitted to NOAA for review)

Neumann, C.J. and J.R. Hope, 1972: A performance analysis of the HURRAN tropical cyclone forecast system. Mon. Wea. Rev., 100, 245-255.

Naumann, C.J., 1975: The effect of initial data uncertainties on the performance of statistical tropical cyclone prediction models. NOAA Tech. Memo. NWS SR-81, 15 pp.

Pellisier, J.M., 1975: Tropical cyclone landfall prediction errors 1970-1974. (Unpublished manuscript, on file at the National Hurricane Center)

Simpson, R.H. and M.B. Lawrence, 1971: Atlantic hurricane frequencies along the U.S. coastline. NOAA Tech. Memo. NWS SR-58, 14 pp.

Sugg, A.L., 1966: The hurricane season of 1965. Mon. Wea. Rev., 94, 187.

Sugg, A.L., 1967: Economic aspects of hurricanes. Mon. Wea. Rev., 95, 143, 146.

Tubb, M., 1974: 1974-75 Directory of marine drilling rigs, Ocean Industry, Gulf Publishing Co., Houston, Texas, 59-127.

Wilson, J.E., 1966: Management. Hurricane Symposium, Amer. Soc. for Oceanography, Publication no. 1, 341, 344.