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A DECISION PROCEDURE FOR APPLICATION IN PREDICTING THE LANDFALL OF HURRICANES

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ABSTRACT

A Bayesian analysis, in real time, is made on the performance of competing numerical and statistical models in predicting the point at which a hurricane will make its landfall on a virtual coastline, 18 and 30 hours following the observations upon which the forecast is based. The results indicate to the hurricane forecaster how each model has performed and will identify the model whose next prediction will have the most dependable basis for a warning decision.

INTRODUCTION

Hurricanes generally move at a deliberate pace and many proceed for days on a regular westerly course during their transit of the Atlantic, With the exception of the offshore area from Florida northward to New England where recurving storms sometimes travel further in 18 hours than in the preceeding 48 hours, persistence (of motion) may be as good a predictor as any hurricane prediction model presently in use, and the penalties of missing a 24-hour forecast by 100 miles or more are rarely large.

However, when a hurricane approaches heavily populated land areas, a miss of a few tens of miles can have the most serious consequences if warnings and evacuations have followed the prediction literally.

The rewards for limiting the coastal extent of warnings are significantly large. Some communities spend millions of dollars implementing preparedness plans when warnings go up, and if the warnings prove unjustified several times in a row, they may well be ignored on future occasions. On the other hand, the cost of limiting the warnings to an area smaller than the expected accuracy of forecasts will support is awesome indeed. Thus, the decision process for predicting the landfall of a hurricane comprises one of the most important operational problems faced by the meteorologist.

This paper is concerned with a Bayesian analysis, in real time, of the performance of competing numerical and statistical prediction models, treated as hypotheses, in predicting the point at which a hurricane will make its landfall on a virtual coastline, 18 and 30 hours following the observations upon which the forecast is based. For both the 18 and 30 hour cases the evidence (or log odds), expressed in decibel units, is computed for each of six prediction methods, including the persistence, based upon the successive verification of the predictions during the course of a hurricane. A computer program was formulated to compute and present the Bayesian statistics and summarize the 18 and 30 hour movement errors in such a form that the forecaster may have a sound basis for deciding which of the methods available to him he should base his decision upon in identifying the landfall position. This program should become an important adjunctive decision tool for use with the series of decision ladders recently developed for the National Hurricane Center by Simpson (1971).

IDENTIFICATION OF A VIRTUAL COASTLINE

In most hurricane warning situations, the point of landfall is far more critical than the timing of arrival. Moreover, the direction of movement is subject to larger variation and probable errors than the speed of movement. For this reason, the emphasis in this paper and the program developed here has focused on the errors in predicting landfall. Since most hurricanes experience only a single landfall, a virtual coastline is defined normal to the observed track at a position 18 hours beyond the time T(0) of forecast initiation. A secondary virtual coastline is defined at a point T(0) + 30 hours. These two positions have been adopted because they represent the most critical decision points (in time) for the forecaster. Considering a normal lag of about six hours in processing data from which a forecast must be made, these time periods furnish the forecaster information in time for critical decision to be made 12 and 24 hours before the hurricane reaches the coastline. At present, specific warnings rarely go up earlier than 12 daylight hours before the hurricane is due at the coastline. However, hurricane watches for specific coastal areas are posted 24 - 30 hours in advance. Since it is the goal of the Warning Service to provide 12 daylight hours of warnings, when the storm is calculated to reach the coast in the early morning hours, it is sometimes necessary to issue specific warnings virtually 24 hours in advance.

The basic input of data comprises the observed movement for three successive 12 hour periods, and the movement predicted by each "hypothesis" or method. The 18 and 30 hour movements and locations of the virtual coastlines are based upon linear interpolations of movement during the second and third 12 hour periods respectively.

The six prediction methods include; (1) Extrapolation, a linear persistence forecast, (2) SANBAR, a barotropic prediction of vortex movement in a deep layer mean circulation, (Sanders and Burpee, 1968), (3) HURRAN, an analog procedure (Neumann and Hope, 1970), adjusted for predicted changes in deviations from normal of the ambient (steering) circulations, (4) NHC-67, a procedure based upon predictors obtained by statistical screening of dynamical circulation properties (Miller, Hill, and Chase, 1968), (5) CLIPER, a stepwise multiple screening regression system using predictors derived from climatology and persistence (Neumann, 1972), and (6) NHC-72, a modified stepwise multiple screening regression system which combines NHC-67 and CLIPER into a single model (Neumann, Hope, and Miller, 1972).

Figure 1 is a schematic example of the computations made by the landfall program for Hurricane Agnes with the initial time T(0) being 0000 GMT June 18, 1972. The construction of the 18 and 30 hour virtual coastlines normal to the actual path of the storm are indicated. The landfall errors are also given for three of the prediction methods (SANBAR, HURRAN and NHC-67). Errors to the right of the actual track are positive and errors to the left are negative.

Several difficulties can arise in the computation of the landfall errors and they will be mentioned briefly. If a forecast begins to parallel the virtual coastline a large landfall error will result and this error will go to infinity when the forecast is exactly parallel. This problem was remedied by setting the landfall error equal to one and one-half times the vector error if the landfall error exceeded the vector error by one and one-half times. If a forecast moves the storm in a direction opposite to the virtual coastline no landfall will result, but a mathematical solution is still possible. Therefore, when a forecast was made moving the storm in the opposite direction to the virtual coastline no landfall error was calculated.

In terms of these two virtual landfalls, the machine program, using the input data for verifications made every 12 hours for the duration of the hurricane, computes (1) the coordinates of observed landfall; (2) the direction, and (3) the speed of movement; (4) the predicted position after 18- and 30-hours by each hypothesis; (5) the landfall error (measured along the coastline); and (6) the vector error for individual forecasts. The accumulative verifications are then summarized to provide (7) mean vector errors; (8) mean landfall errors; (9) mean bias (to right or left of observed landfall); (10) the standard deviation; and finally, (11) the Bayesian evidence in decibels for each of the six prediction methods. The output of the program is shown in Figures 2, 3, and 4.

COMPUTATION OF EVIDENCE

Bayes equation may be written in what is sometimes called the log-odds form, (e.g., Goode, 1950), but is appropriately termed by Tribus, (1969) the Evidence. In this form, Bayes equation is:

$$ev(A|C) = 10 \log_{10} \frac{p(A|C)}{p(a|C)} \qquad (1)$$

using the notation of Tribus in which a is the denial of A and C is the conditional information upon which the truth of A depends.

The application of this equation to the decision problem at hand involves the comparative measure of performance for prediction methods in terms of observed errors and we may write

$$ev(H_i|F_n D_n X) = 10 \log_{10} \frac{p(H_i|F_n D_n X)}{p(h_i|F_n D_n X)} \qquad (2)$$

and by extending the conversation

$$ev(H_i|F_n D_n X) = 10 \log_{10} \frac{p(H_i|X)\, p(D_n|F_n X)}{p(h_i|F_n D_n X)} \qquad (3)$$

Where

- H_i = the prediction according to H_i is the most reliable.
- F_n = the prediction made
- D_n = the verification data
- X = other knowledge about the verification procedures.

Here the term $p(H_i/X)$ is the prior probability and the term $p(D_n/F_nX)$ is the error probability. Since separate error probabilities will be computed for each hypothesis, or prediction method, it is convenient to normalize equation (3) in the following way. If

$$P(i) = p(H_i|X)\, p(D_n|F_n X)$$

and

$$P(o) = \sum_{i=1}^{i=6} P(i)$$

Then (3) may be rewritten

$$ev(H_i|F_n D_n X) = 10 \log_{10} \left(\frac{P(i)/P(o)}{1 - P(i)/P(o)} \right) \qquad (4)$$

and

$$ev(H_i|F_n D_n X) = 10 \log_{10} \left(\frac{P(i)}{P(o) - P(i)} \right) \qquad (5)$$

Which is the form used in computation.

The error distribution or probability about the forecasted position is taken to be a normal distribution centered at the forecasted position (zero mean error) described by the current landfall error and a long term standard deviation of the landfall error which varies from one model to another.

$$p\left(D_n \mid F_n X\right) = \frac{1}{\sqrt{2\pi}\,\sigma_i} EXP\left[(-.5)\left(E2/\sigma_i\right)^2\right] \quad (6)$$

Where E2 = current landfall error

σ_i = long term standard deviation of the landfall error for each individual prediction method.

Table 1 gives the long term standard deviations of the landfall errors for 18 and 30 hours for the six hypotheses. These were computed using 1971 forecast data. The CLIPER and NHC-72 hypotheses have the standard deviations of the HURRAN and NHC-67 hypotheses respectively because these techniques were begun in 1972.

The assignment of prior probabilities was done more subjectively. Table 2 gives the prior probabilities used in the program.

This says that, *a priori*, there is one chance in ten that EXTRAPOLATION will be the best predictor, and that the other hypotheses are equally likely.

The evidence supporting each hypothesis serves as a yardstick as to the probable worth of the next prediction by each method, the one with the larger final figure nominally representing the favored technique. However, the trends over an interval of 2 - 4 periods will carry significant information which may be projected under certain circumstances. For example, the performance of NHC-67 may be quite poor in very low latitudes or near Mexico, and an upward trend in evidence exhibited as the storm moves into more favorable areas may well imply a superiority of this hypothesis for the next forecast, even though the terminal decibel value may be somewhat less than for another hypothesis which shows no decided trend or a retrogression.

Also, on some occasions there may be a clustering of results with little trend in evidence. This will reflect uncertainty of all the predictions and a larger margin for error in posting warnings will be indicated.

However, the primary purpose of this computation is to identify the one hypothesis whose next prediction will be the most dependable basis for a warning decision. When this is accomplished, the forecaster will adopt the policy of using the results of this hypothesis alone to determine the landfall and to determine the requirement for warnings. There is no basis in reason for applying these results to obtain some solution intermediate between two or more of the hypotheses, even though aside from the competitive hypotheses the forecaster always retains a judgmental override authority.

Clearly, the evidence provided through this computation falls short of a dynamical insight (in real time) to the strengths and weaknesses of the six prediction methods. However, the information thus obtained on the apparent relative strengths will serve as the starting point for post-season critiques of forecasts which can than identify the dynamical frailties of each method.

In addition to the Bayesian evidence for each hypothesis, the verification summary generated by this program provides other means of assessing the performance of each method. Comparisons of the vector mean and landfall mean errors indicate the reliability of speed predictions. The bias figures will indicate whether the errors are random or systematic, and the standard deviation will point to the dependability of the mean errors. It should be pointed out that these verifications are concerned with the actual displacement of the pressure center, and no attempt is made here to deal with positioning errors which are a separate but important problem contributing to the warning errors.

CONCLUSIONS

This example of a machine program to process and organize information on the performance of competing hurricane prediction methods illustrates how Bayesian analyses may be combined with other statistical parameters to supply a basis for sound decisions on critical forecast problems. It is expected that this initial effort will open up many new avenues for applying decision and information analyses to the more formidable and intractable weather prediction problems, especially those of the tropics.

ACKNOWLEDGEMENTS

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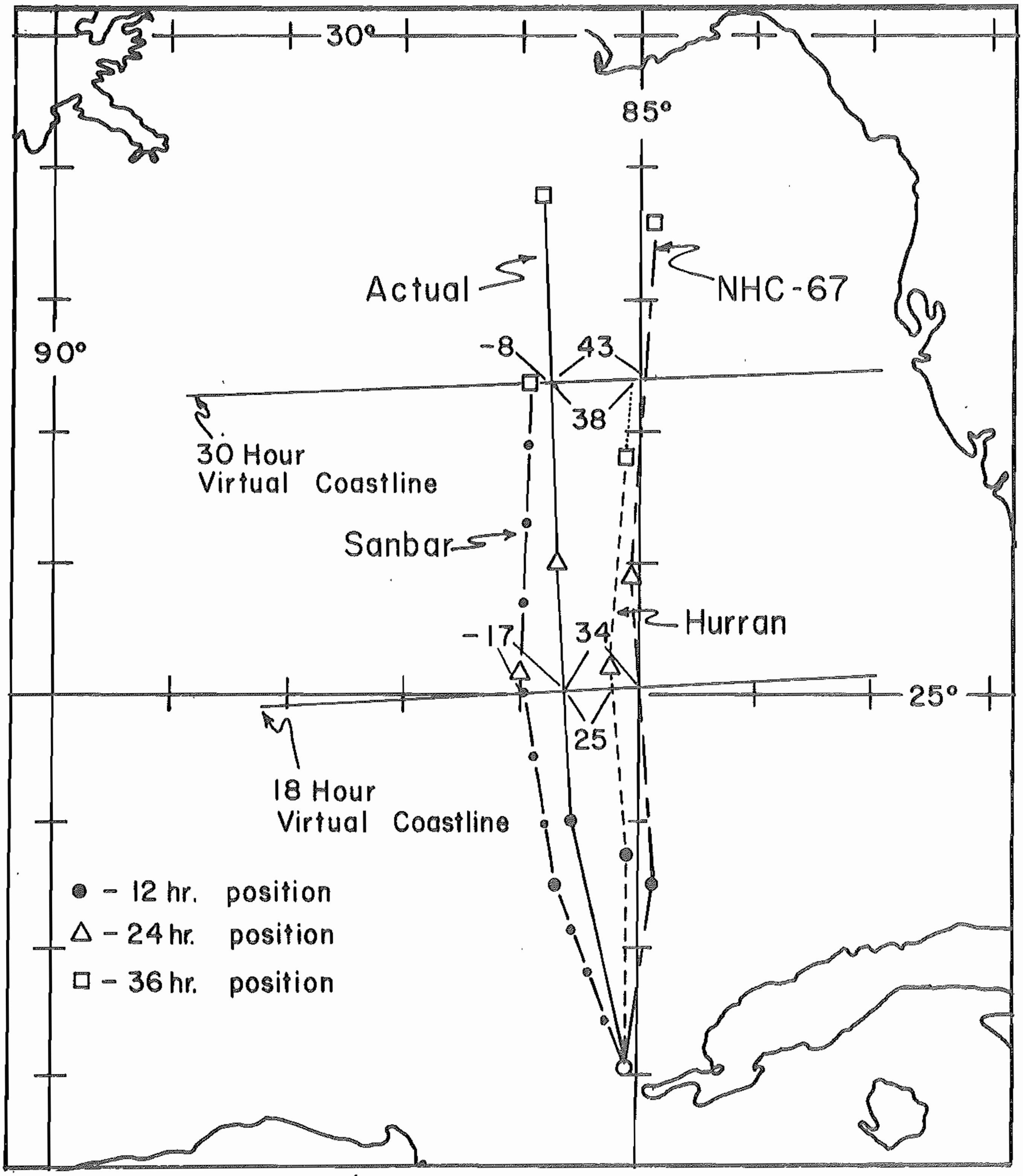

Figure 1. Diagram of the actual track, 18 and 30 hour virtual coastlines, tracks of three prediction models (SANBAR, HURRAN, and NHC-67), and the landfall errors in nautical miles for hurricane Agnes. Initial time is 18 June 1972 at 0000 GMT. The 18 and 30 hour coastlines correspond to 1800 GMT 18 June and 0600 GMT 19 June respectively.

THE MONTH AND YEAR ARE JUNE 1972

OBSERVED LANDFALL OF HURRICANE AGNES
AT A VIRTUAL COASTLINE WITH ERRORS IN
PREDICTED LANDFALL POSITIONS

PREDICTIONS BASED UPON OBSERVATIONS AT	18/0000Z
INITIAL POSITION OF CENTER	22.1 N 85.1 W

OBSERVED 18- HR MOVEMENT

VALID TIME FOR FORECAST	18/1800Z
LANDFALL POSITION AT VIRTUAL COASTLINE	25.0 N 85.6 W
DISTANCE TO VIRTUAL COASTLINE	176.6 N. MI.
AVERAGE DIRECTION OF MOVEMENT	350.1 DEG.
AVERAGE SPEED OF MOVEMENT	9.8 KTS.

OBSERVED 30- HR MOVEMENT

VALID TIME FOR FORECAST	19/0600Z
LANDFALL POSITION AT VIRTUAL COASTLINE	27.4 N 85.7 W
DISTANCE TO VIRTUAL COASTLINE	320.0 N. MI.
AVERAGE DIRECTION OF MOVEMENT	353.6 DEG.
AVERAGE SPEED OF MOVEMENT	10.7 KTS.

PREDICTED POSITIONS FROM T(0) 18/0000Z

SOURCE	T(0)+18-HR		VEC ERR	T(0)+30-HR		VEC ERR
EXTRAP	23.6 N	85.1 W	88.9	24.6 N	85.1 W	171.3
SANBAR	24.4 N	85.8 W	40.5	26.3 N	85.9 W	66.9
HURRAN	24.5 N	85.2 W	42.5	26.0 N	85.2 W	89.8
NHC-67	24.7 N	85.0 W	39.7	27.2 N	85.0 W	41.0
CLIPER	24.5 N	85.0 W	46.3	26.9 N	84.9 W	54.6
NHC-72	24.5 N	85.0 W	46.4	25.9 N	84.9 W	103.6
OFFICIAL	24.2 N	85.2 W	52.6	26.0 N	84.7 W	99.6

VIRTUAL LANDFALL PREDICTION ERRORS (N. MI.)

SOURCE	18-HOUR	30-HOUR
EXTRAP	28.8	32.8
SANBAR	-16.5	-8.3
HURRAN	24.7	37.7
NHC-67	34.1	42.8
CLIPER	43.4	48.1
NHC-72	44.1	33.6
OFFICIAL	36.4	74.7

Figure 2. Computer output of the landfall program.

SUMMARY OF 18-HOUR VIRTUAL LANDFALL ERRORS FOR AGNES

T(O)	T(1)-VALID	EXTRAP	SANBAR	HURRAN	NHC-67	CLIPER	NHC-72	OFFICIAL
16/12	17/06	68.6	-176.9	999.9	-101.7	-108.7	-142.2	-20.2
17/00	17/18	135.9	999.9	999.9	999.9	96.3	999.9	98.5
17/12	18/06	45.6	-41.8	23.0	22.6	21.0	17.7	24.7
18/00	18/18	28.8	-16.5	24.7	34.1	43.4	44.1	36.4

SUMMARY OF 30-HOUR VIRTUAL LANDFALL ERRORS FOR AGNES

T(O)	T(1)-VALID	EXTRAP	SANBAR	HURRAN	NHC-67	CLIPER	NHC-72	OFFICIAL
16/12	17/18	142.3	-173.5	999.9	-104.5	-162.2	-214.8	-23.5
17/00	18/06	-289.4	999.9	999.9	999.9	91.5	999.9	76.3
17/12	18/18	134.5	-39.2	21.1	54.7	60.3	-64.2	22.6
18/00	19/06	32.8	-8.3	37.7	42.8	48.1	33.6	74.7

18-HOUR PREDICTION VERIFICATION SUMMARY FOR AGNES
ACCUMULATIVE MEAN ERRORS

SOURCE	VECTOR	LANDFALL	BIAS	STD DEV	CASES
EXTRAP	68.2	69.7	69.7	40.7	4
SANBAR	66.5	78.4	-78.4	70.4	3
HURRAN	38.0	23.9	23.9	.9	2
NHC-67	52.0	52.8	-15.0	34.9	3
CLIPER	53.5	67.4	13.0	36.3	4
NHC-72	52.6	68.0	-26.8	53.6	3
OFFICIAL	51.8	45.0	34.8	31.5	4

30-HOUR PREDICTION VERIFICATION SUMMARY FOR AGNES
ACCUMULATIVE MEAN ERRORS

SOURCE	VECTOR	LANDFALL	BIAS	STD DEV	CASES
EXTRAP	145.0	149.8	5.0	91.5	4
SANBAR	93.2	73.7	-73.7	71.7	3
HURRAN	55.6	29.4	29.4	8.3	2
NHC-67	75.8	67.3	-2.3	33.6	3
CLIPER	96.9	90.5	9.4	62.9	4
NHC-72	109.4	104.2	-81.8	100.3	3
OFFICIAL	90.5	49.3	37.5	38.9	4

Figure 3. Computer output of the landfall program. The 999.9 indicates a missing forecast.

BAYESIAN EVIDENCE (DECIBELS) FROM FORECASTS FOR AGNES
SUPPORTING EACH PREDICTION METHOD 18-HOUR

T(O)	T(1)-VALID	EXTRAP	SANBAR	HURRAN	NHC-67	CLIPER	NHC-72
16/12	17/06	-5.7	-7.0	999.9	-4.3	-3.9	-11.9
17/00	17/18	-6.5	999.9	999.9	999.9	6.5	999.9
17/12	18/06	-13.3	-8.6	-6.2	-5.5	-6.1	-5.4
18/00	18/18	-12.5	-7.8	-5.7	-5.6	-6.5	-6.2

BAYESIAN EVIDENCE (DECIBELS) FROM FORECASTS FOR AGNES
SUPPORTING EACH PREDICTION METHOD 30-HOUR

T(O)	T(2)-VALID	EXTRAP	SANBAR	HURRAN	NHC-67	CLIPER	NHC-72
16/12	17/18	-9.5	-4.7	999.9	-1.7	-6.0	-13.6
17/00	18/06	-11.9	999.9	999.9	999.9	11.9	999.9
17/12	18/18	-14.5	-8.3	-5.4	-5.5	-6.2	-5.9
18/00	19/06	-13.4	-8.6	-6.1	-5.5	-6.3	-5.3

Figure 4. Computer output of the landfall program.
The 999.9 indicates a missing forecast.

Table 1. Long term standard deviations of the 18 and 30 hour landfall errors in nautical miles for each model.

SOURCE	18-HOUR	30-HOUR
EXTRAP	88.4	163.8
SANBAR	102.1	177.0
HURRAN	65.6	102.8
NHC-67	57.3	88.3
CLIPER	65.6	102.8
NHC-72	57.3	88.3

Table 2. Prior probabilities used for each model.

SOURCE	18-HOUR	30-HOUR
EXTRAP	.10	.10
SANBAR	.30	.30
HURRAN	.30	.30
NHC-67	.30	.30
CLIPER	.30	.30
NHC-72	.30	.30

REFERENCES

Good, I. J., 1950: Probability and the Weighing of Evidence, Hafner Publishing Company, New York

Hope, J. R., and C. J. Neumann, 1970: "An Operational Technique for Relating the Movement of Existing Tropical Cyclones to Past Tracks", Monthly Weather Review, Vol. 96, pp. 925-933.

Miller, B. I., Elbert Hill, and Peter Chase, 1968: "Revised Technique for Forecasting Hurricane Movement by Statistical Methods", Monthly Weather Review, Vol. 96, pp. 540-548.

Neumann, C. J., 1972: "An Alternate to the HURRAN Tropical Cyclone Forecast System", NOAA, Technical Memorandum NWS SR-63, 32 pp.

-------, and J. R. Hope, and B. I. Miller., 1972: "A Statistical Method of Combining Synoptic and Empirical Tropical Cyclone Prediction Systems", NOAA, Technical Memorandum NWS SR-63, 32 pp.

Sanders, F. and R. W. Burpee, 1968: "Experiments in Barotropic Hurricane Track Forecasting", Journal of Applied Meteorology, Vol. 7, No. 3, pp. 313-323.

Simpson, R. H., 1971: "The Decision Process in Hurricane Forecasting", NOAA Technical Memorandum NWS SR-53, 35 pp.

Tribus, Myron, 1969: Rational Descriptions, Decisions, and Designs, Pergamon Press, New York