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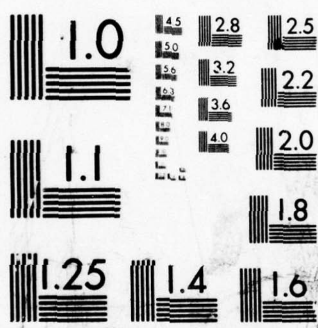

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LEVEL II

A TECHNIQUE FOR USING SYNOPTIC ANALOGS TO PREDICT THE DEVELOPMENT OF TROPICAL DEPRESSIONS INTO NORTH ATLANTIC HURRICANES

A Thesis

by

DAVID ALAN GRIMM

Submitted to the Graduate College of
Texas A&M University
in partial fulfillment of the requirement for the degree of

MASTER OF SCIENCE

May 1979

Major Subject: Meteorology

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A Thesis

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May 1979

ABSTRACT

A Technique for Using Synoptic Analogs to Predict the Development of Tropical Depressions into North Atlantic Hurricanes. (May 1979)

David Alan Grimm, B.S., Texas A&M University

Chairman of Advisory Committee: Professor W. K. Henry

This study presents a method for using the output of the U.S. Navy long range (analog) forecast model to predict the development of tropical depressions in the North Atlantic Ocean into tropical storms or hurricanes. The technique is applied to North Atlantic tropical depressions which formed in the period from 1974 through 1977. Sample cases, statistical analyses of results, and verification of the technique are presented. Results show that the method successfully predicts tropical depression development. Recommendations are made to streamline and improve the technique.

ACKNOWLEDGMENTS

I would like to express my appreciation to the following individuals and organizations for their help and inspiration during this program of study:

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Ms. Joyce A. Fox, for her understanding and inspiration.

DEDICATION

To

Joyce

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1. INTRODUCTION

Every year there are many tropical disturbances in the North Atlantic Ocean, but only rarely does one develop into a hurricane (Holton, 1972). Currently, the prediction of which disturbance will develop is not possible. One of the biggest obstacles in being able to produce a numerical model that can make a reasonably accurate prediction of hurricane development is the difficulty of attaining adequate observations in the early stages of development (Palmen and Newton, 1969). As will be shown later, recent events indicate that even an increase in observations may not be sufficient to explain why some depressions develop into hurricanes and some do not.

It was with a full appreciation of the complexity involved when forecasting hurricane development, that a synoptic analog approach was chosen to attack the problem. Synoptic analog forecasting does not attempt to explain why a weather event occurs, but rather attempts to isolate those synoptic situations in which the event occurred, and when isolated, forecast a repeat of the occurrence.

As a simple example of how a synoptic analog forecasting scheme works, suppose that on a given day a cold front was located north of a station. A forecaster finds a number of historical weather maps which contain a similar cold front. By advancing chronologically through his historical maps, he notes that most of the similar cold fronts moved past his station. He would, using only synoptic analogs, most likely

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forecast the current front through, also. In this manner, postulating that he has no knowledge of why the front moves, he still is able to make a reasonably accurate forecast.

It is obvious that this type of forecasting should be considered as an interim method. As more and more knowledge is gained about tropical disturbance development, the probability of a breakthrough in a forecasting technique improves. But in the meantime, a synoptic analog approach for forecasting hurricane development was considered worthy of study.

2. BACKGROUND

Hurricane forecasting generally is confined to one of three areas: (1) development, (2) intensification, or (3) movement. More advances have been made in forecasting hurricane movement than intensification, and there has been very little success in forecasting development. However, an analog approach has been invaluable in the evolution of methods to understand better and forecast each of the three.

a. Movement

Forecasting the movement of these storms traditionally has received the largest portion of the research because of the enormous damage and loss of life that can occur if the affected areas are not warned properly. For example, between the years 1900 and 1960, 17,000 persons lost their lives in the United States due to hurricanes, and the associated property damage amounted to 5 billion dollars (Maunder, 1970).

Consequently, the National Hurricane Center (NHC) has developed a number of statistical models to predict hurricane movement. One of the most successful of these models is the HURRAN (HURRicane ANalog) developed by Hope and Neumann (1970). This model employs a computer scan of 703 documented tropical cyclone tracks dating back to 1886. The model searches for those tracks with time and space characteristics similar to the current storm. Ellipses of probability of position are plotted and Neumann (1974) states that it is NHC policy that the official track forecast must fall within the bounds of the 50% probability ellipse for a given forecast time. For example, the 48 hour track forecast must pass through the HURRAN 50% probability ellipse around that point.

The United States Navy also has relied on synoptic analogs to forecast the tracks of typhoons in the Pacific Ocean. For the Western North Pacific Ocean, an analog technique called TYFOON-3 was formulated by Hodge and McKay (1970) and subsequently modified by Jarrell and Somervell (1970) and Jarrell and Wagoner (1973). The movement of a typhoon in the southeastern North Pacific is forecast by using a similar technique developed by Jarrell et al. (1975).

b. Intensification

Unlike the considerable use of analogs to provide objective guidance in forecasting tropical cyclone movement, the techniques for forecasting changes in intensity primarily are subjective, based on climatology, upper-air analyses, sea-surface temperatures, and other considerations (Atkinson, 1971). However, some research has been initiated to use analogs to offer an objective input for intensity forecasts. Wagoner (1973) developed a technique for using analogs to forecast central pressures of tropical cyclones in the North Pacific. The technique produced forecasts that were comparable to those issued by the official warning agency. Foster (1973) also used analog data for the North Pacific to develop a scheme for predicting tropical cyclone intensification and the resultant wind speed increases. Verification against official forecasts was termed "encouraging." Elsberry (1974) used statistical regression equations to forecast intensity changes with results which appear to have equal or better accuracy than the subjective forecasts by standard means.

More recently, satellite data have been used to try to estimate tropical cyclone intensity and forecast subsequent changes. Dvorak (1975) developed a method for using satellite photographs to identify characteristic cloud patterns in tropical cyclones and, by matching these patterns to previous storms, estimate the current strength of the storm and predict its intensification.

c. Development

Even though there has been moderate success in forecasting tropical cyclone movement and some success in forecasting intensification, there has been no success in forecasting initial development. According to Garstang (1972), the reason for this is, "Despite knowledge gained on the 'necessary' conditions for hurricane development and the subsequent description of the mature storm, specification of the sufficient condition or conditions remains as elusive as ever."

Even our knowledge of the necessary conditions for hurricane development is being debated. Atkinson (1971) summarizes the views of Palmén, Riehl, Gray, Charney, and Eliassen as follows: (1) Palmen lists the necessary conditions as sea-surface temperature of more than 26° or 27°C, a weak vertical wind shear in the basic current, and a location more than 5° to 8°N to insure an adequate Coriolis force; (2) Riehl added to the above three conditions the need for a pre-existing low-level disturbance and a region of upper-level divergence or outflow above the surface disturbance; (3) Gray disagrees with the need for a pre-existing upper-level region of divergence and feels that this upper-level divergence occurs as a result of the low-level convergence caused by the frictional veering of the wind in the planetary boundary layer; and (4) Charney and Eliassen somewhat disagree with Riehl and speculate that development occurs in a region with "conditional instability of the second kind" (CISK).

There is, however, general acceptance that necessary conditions include, but are not limited to, Palmén's original three and Riehl's requirement for a pre-existing low-level disturbance. This, of course, does not allow accurate forecasts of hurricane development, but it does allow delineation of areas of the globe which are conducive to development. Studies such as that done by Gray (1968) have been very important in isolating areas of potential development. Gray studied over 300 development cases and reaffirmed that formation occurred only where the sea-surface temperature was greater than 26.5°C, the location was at least 5° to 8°N or S of the equator, and in an area where the tropospheric vertical shear of the wind is at a minimum.

Another climatological and statistical technique developed by Ballenzweig (1957) and updated by Herbert and Miller (1969) indicates which geographical areas of the eastern and southeastern United States have a greater or lesser vulnerability to tropical cyclones during a given circulation regime. It was shown that there exists a relationship between the 700 mb planetary wave pattern and height anomalies and the development and movement of North Atlantic tropical cyclones.

More recently, researchers have begun to examine observational and satellite data to try to isolate those meteorological conditions which are present in the case of the developing disturbance and missing or noticeably weaker when similar systems do not develop. Erickson (1977) used Defense Meteorological Satellite Program pictures and rawinsonde data in such a study. The largest difference he found while studying developing and non-developing storms was that the disturbances which developed had a larger cirrus-level outflow, greater low-level vorticity, and a weaker vertical wind shear.

Another observational study done by Reeves and Ropelewski (1977) appears to have more far reaching implications. As was pointed out in the introduction, the lack of sufficient observational data in the early stages of storm development is thought to be one of the biggest obstacles to the production of a prediction model. A rare opportunity to obtain such data occurred during the GARP Atlantic Tropical Experiment during the summer of 1974. As part of this experiment, an unusually dense network of scientific ships was located off the western coast of Africa near Dakar, Senegal. A tropical disturbance began to form near the fleet and its characteristics were recorded using rawinsonde, radar, and surface observations. This disturbance developed into tropical storm Alma shortly after the observations were taken. Six other similar disturbances that did not further develop were investigated, also. After analyzing the data associated with tropical storm Alma, Reeves and Ropelewski found that, ". . . its kinematic properties were not unique when compared with six non-developing disturbances."

d. Summation

This background information is not intended to be a comprehensive review of the work done in the field of hurricane forecasting. Noticeably, references to the research done in dynamic modeling have been omitted as they are not germane to this work. Instead, this background is provided to give the reader some appreciation of the extremely complicated interactions that must take place in the atmosphere in order for a tropical disturbance to develop into a hurricane. Also, it is intended to acquaint the reader with some of the success that has been attained using analogs to predict tropical cyclone movement and intensification.

3. DATA

In order to develop a synoptic analog forecasting scheme, three types of data are required. First, it is necessary to construct a list of dates on which the weather event to be forecast has occurred. For the purpose of this study, it was determined that this event would be a tropical depression. By standard definition, this is a weak tropical cyclone with a definite closed circulation and maximum sustained wind speeds of less than 34 knots. Next, a method of isolating similar synoptic situations must be devised. And finally, sufficient historical maps to check the analog cases must be found.

a. Depressions

Daily 1200 GMT latitude and longitude positions for all tropical depressions which formed in the North Atlantic Ocean during the period from 1974 through 1977 were taken from the works of Frank and Gilbert (1978, 1977) and Frank (1976, 1975). All positions were recorded to the nearest 0.5°. Information pertaining to their future development or dissipation was taken from the works of the above authors as well as Lawrence (1978, 1977), Herbert (1976), and Hope (1975).

b. Analogs

The analog data have been supplied by the U.S. Navy Fleet Numerical Weather Central (FNWC) from the output of their automated long range (analog) forecast model (McConathy and Thormeyer, 1974). The CDC computer searches the FNWC data base of historical maps, from 1946 to the present, at the 1000 and 500 mb levels to find synoptic situations most closely resembling current weather patterns. The average correlation coefficients for the match of the large scale 500 mb features and the 1000 mb level are determined. These coefficients are an indication of the closeness of the match of the current 500 and 1000 mb features to those in the historical data bank. A detailed description of the process used to determine these correlation coefficients is presented in Appendix A. After this process, the 40 best matches (analogs) are then identified by date. Correlation coefficients are given for the area north of 20°N for the Northern Hemisphere and separately for the areas north of 20°N and between 40°W to 130°W, 130°W to 160°E, 160°E to 60°E, and 60°E to 40°W. These correlation coefficients can range from a value of +1.000 (perfect correlation) to -1.000 (perfect negative correlation). Printouts for the 40 best analog matches were provided to cover the periods from June through October 1974, June through September 1975, June through September 1976, and June through September 1977. However, since the model is used mainly for Navy long range forecasting, the data are available on every third or fourth day of the period mentioned and this constitutes one of the data screens that will be discussed later. A typical sample of the bulletin is shown in Fig. 1.

c. Historical Maps

In order to make the analog matches, surface weather maps for the corresponding match dates had to be found to cover the period from 1946 through 1976. Also, the maps must have a 1200 GMT valid time since both the depression positions and the analog bulletins are valid at that time. The U.S. Department of Commerce Northern Hemispheric daily

MESSAGES PRODUCED FOR CARSWELL, FROM 3200 TAPE DTG = 76060700.

ABXN KNWC 070000 A66 0
ANALOG DATES MESSAGE - FOR METEOROLOGIST ONLY

1. ANALOGS LISTED BELOW MATCH THE CURRENT DTG OF 76060612

2. QUALITY OF BEST ANALOGS VS. INITIAL MATCH---
(AVERAGE OF SL 500 AND SR 1000, RANGE CAN BE FROM -1.000 TO +1.000). LAST COLUMN INDICATES THOSE DATES ACCEPTED (YES) FOR COMPOSITE ANALOG.

BEST DATES YYMMDDHH	HEMIS 360 DEG	N. AMER. 40W-130W	PACIFIC 130W-160E	WESTPAC 160E-60E	ELANT/MED 60E-40W	ACCP COMP
65052212	.6990	.7161	.6282	.7298	.6021	NO
46060812	.7468	.5768	.6195	.8192	.8093	YES
46060912	.7112	.5646	.6337	.6926	.7341	NO
46062312	.6842	.7329	.6228	.4645	.6914	NO
46062412	.7152	.7213	.6197	.6268	.6738	NO
46062512	.7024	.5864	.5584	.6907	.7201	NO
46062612	.7306	.6238	.5862	.7566	.7612	YES
46062712	.6822	.7028	.3441	.6892	.7532	NO
47062412	.7034	.7094	.6528	.6385	.6955	NO
47062512	.6803	.5349	.5209	.7235	.6815	NO
48061412	.6906	.1868	.5957	.8246	.8288	NO
48061512	.6979	.2474	.5116	.8819	.8787	NO
50060812	.6986	.7478	.4899	.6753	.6151	NO
55062712	.6902	.6889	.4694	.7336	.7514	NO
55062812	.7045	.7098	.3873	.6552	.7861	NO
55062912	.6890	.6007	.3801	.7079	.8025	NO
55063012	.7278	.5129	.5557	.8526	.8101	NO
56060312	.7210	.7084	.5829	.7113	.6755	YES
56060412	.6882	.6655	.4997	.6663	.5847	NO
60062012	.6897	.5870	.6354	.7948	.6563	NO
60062112	.7002	.5609	.6680	.7779	.6799	NO
61062912	.7326	.7851	.4856	.5935	.7825	NO
61063012	.7382	.7316	.6185	.5205	.8596	YES
62061112	.7011	.5887	.5509	.7970	.7047	NO
62061212	.7501	.6746	.5848	.8310	.7518	YES
62061312	.7634	.7470	.6683	.7611	.7416	YES
62061412	.7373	.7305	.5433	.7178	.7669	YES
64062612	.7058	.7331	.5274	.7451	.6133	NO
65061712	.6867	.6790	.4138	.8573	.6071	NO
65061812	.6830	.6822	.4458	.8191	.6195	NO
46070612	.6758	.7326	.4446	.5653	.6897	NO
50070412	.7131	.6930	.5335	.6333	.7956	NO
55070212	.7590	.7139	.6277	.8064	.7343	NO
55070312	.7829	.7979	.7185	.7423	.7268	YES
55070412	.7625	.7710	.6645	.7436	.7061	YES
55070512	.7134	.7350	.5114	.7379	.6711	NO
69070112	.7010	.7096	.3936	.7624	.7637	NO
71070212	.7310	.7182	.6072	.7253	.7797	YES
71070312	.7312	.7212	.6574	.7322	.7237	NO
71070412	.7081	.6215	.6064	.6955	.7236	NO

Fig. 1. Typical analog bulletin.

series of synoptic weather maps, Part I, were used for the periods from 1949 through 1956 and 1959 through 1969. The 1946 through 1948 and 1957 through 1958 historical maps were not available in the Texas A&M collection nor were any suitable substitute maps. For the period from 1970 through 1976, the Republic of Venezuela's daily series, Boletin Meteorologico Diario were used. These maps cover an area from 40°W to 100°W and 5°S to 40°N.

4. PROCEDURES

a. Data Screens

Because of the irregularity of the run times of the analog bulletins and their availability only for selected months, certain restrictions (screens) had to be placed on the tropical depression data. Since the analog data were available only for a limited number of months, any depression which formed before June or after October 1974, or did not form during June through September 1975, 1976, or 1977 was rejected. A second screen was determined by the area of interest for this study. A separate correlation coefficient is provided on the analog bulletin (Fig. 1) for the area entitled North America, 40°W to 130°W. It was, therefore, decided to limit the tropical depressions to those which formed in an area from 40°W to the western edge of the Gulf of Mexico and north of 20°N. The area of interest is shown in Figure 2. If, however, a depression formed outside of this area and subsequently moved into the area and retained its tropical depression characteristics, it was considered as part of the data set. The final screen was set so that for a tropical depression position to be usable, an analog bulletin date must match the tropical depression position date. For example, if a tropical depression was found in the area of interest on July 10, 1976, an analog bulletin must exist with the same date.

The application of these screens reduced the size of the data set considerably. During the period from 1974 through 1977, 95 tropical depressions formed in the North Atlantic Ocean. Of these, 21 depres-

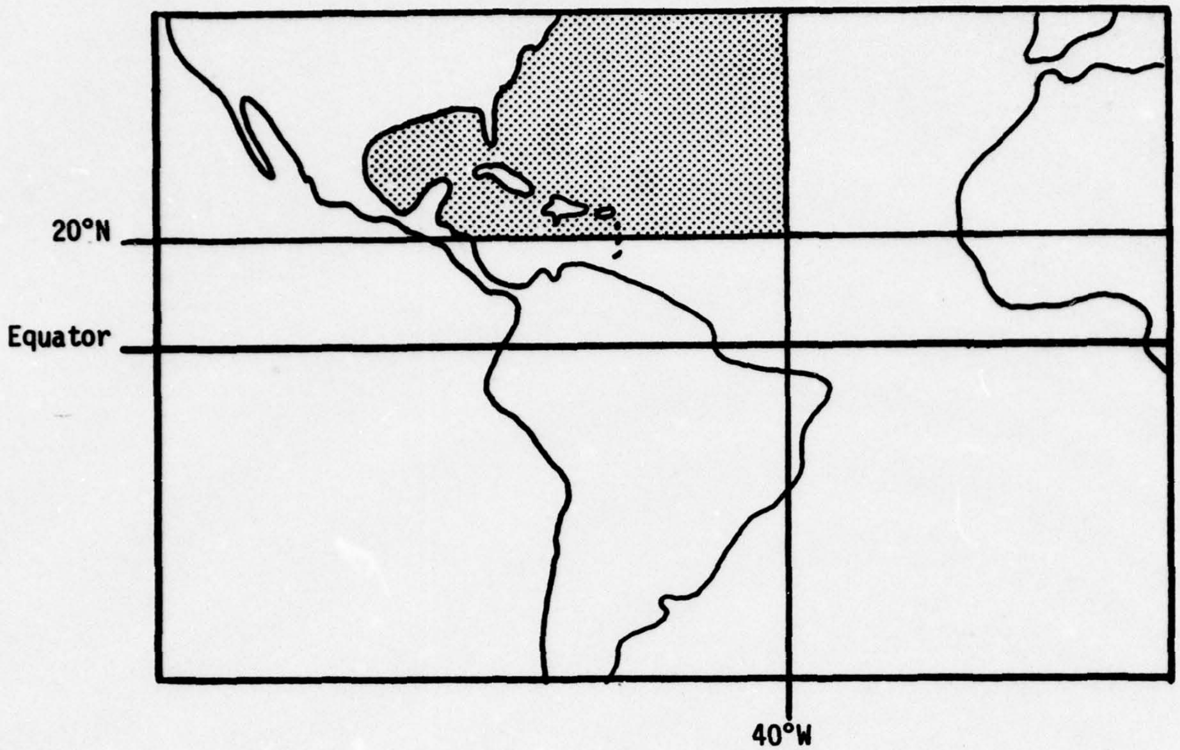

Fig. 2. Tropical depression data area. All of the tropical depressions used in this study were confined to the region depicted by the stippling.

sions were eliminated because they did not occur within the available analog bulletin months. An additional 23 depressions were eliminated because they formed and remained outside of the area of interest (10 remained east of 40°W and 13 remained south of 20°N). This left a total of 51 depressions which passed the first three screens.

For these remaining 51 depressions, a total of 148 1200 GMT latitude and longitude positions were recorded along with the date of the position fix. Each date was compared to the available analog bulletin dates. Because some of the depressions remained for many days (the longest lasted 8 days), a few of the depressions received more than one analog match. In the extreme case of the depression which lasted eight days in 1976, a separate analog match was available for its position on September 22 and 26. As a result, for the remaining 51 depressions, 28 had at least one analog match and four had two matches. Of these 28 remaining depressions, five developed into hurricanes and three into tropical storms. Only one hurricane, Caroline in 1975, had two analog matches.

The final data screening problem occurred because of the non-availability of some historical maps. Since the remaining 28 depressions had a total of 32 analog matching bulletins and there are 40 analog matches on each bulletin, there should have been 320 historical map cases for the depressions that did develop and 960 cases for those that did not. The actual number of cases available is shown in Table 1. In this table, the term "miscellaneous missing" refers to the occasional lack of a Venezuelan analysis that had been annotated as "NIL", the non-availability of October 1953 historical maps in the local collection, and missing maps from late July through early August in the Venezuelan series. From the expected 1280, a total of 1197 analog matches remained to be reviewed.

Table 1. Available and missing analog matches.

Year	Available	Missing 1946-1948	Missing 1957-1958	Miscellaneous missing	Sub-total
1977	115	3	0	2	120
1976	319	31	4	6	360
1975	205	27	8	0	240
1974	498	46	9	7	560
Total	1197	107	21	15	1280

b. Basic Technique

The tropical depression stage of development was chosen to more precisely isolate the type of weather event to be investigated. Since, by definition, the depression has a closed circulation, a surface low pressure area of tropical origin found on a historical map would most characteristically resemble the depression. Also, since the depressions were documented as to their positions, an orderly search could be assured for similar low centers in the historical map series.

For each depression with an analog match, all 40 match candidate dates were reviewed manually to find a similar low center located in the general vicinity of the actual depression's position. The outside distance limit for finding a similar low center was established such that the analog match low must be within a circular area whose radius was 7° of latitude, or approximately 420 n mi. This corresponds to a maximum oceanic area of about 550,000 n mi^2 in which to find the match.

The basic technique was to find a depression position with an analog match date. Then, by proceeding through the 40 match candidates on the analog bulletin, each of the match dates on the bulletin was checked in the historical map series to find a similar low center within the prescribed maximum circular area. If a similar low center was found for a given analog match date, the date of the match, North American correlation coefficient, latitude/longitude position, and distance from the actual depression position in nautical miles were recorded. Next, by advancing chronologically through the historical maps, it was determined whether or not the analog match low center developed to either the tropical storm or hurricane intensity level. If development did take place, the number of days it took the low to reach each intensity level was recorded. Since the scheme was to be used to predict development, each time the analog match produced a tropical storm or hurricane already in progress where a depression was being sought, this was similarly recorded with an appropriate notation.

This procedure of taking a bulletin, checking all 40 analog matches by reviewing the historical maps, and recording applicable matches continued through all 32 depression match bulletins and the corresponding 1197 historical maps. To eliminate possible bias in the review, the maps were checked with only the depressions' latitude and longitude positions, and with no information about their future development.

c. Necessary Assumptions

As was pointed out in the background section, general agreement exists that necessary conditions for the development of tropical cyclones includes the need for a pre-existing disturbance, a location north of 5 to 8°N, a weak vertical wind shear, and sea-surface temperatures of more than 26° or 27°C. Since these are the conditions generally accepted as necessary for development to occur, it was felt that it would not be sufficient to only have good correlation between synoptic patterns, but that an attempt would have to made to satisfy all four conditions as well. For this study, the first two of these conditions were satisfied easily. One of the procedures used in this research was to find a similar pre-existing disturbance and, because the Navy analog grid begins at 20°N, all analog match low centers were located north of 20°N. The other two necessary conditions had to be assumed to be met. The need for a weak vertical wind shear should be satisfied by the analog matching process. Since the match is for both the 1000 and 500 mb levels, there is some implicit information about the vertical wind shear and thermal structure between these levels. A good analog match will indicate historical maps with similar 1000 and 500 mb fields and, therefore, a similar vertical shear. The sea-surface temperature, however, posed an entirely different problem. It was assumed that the sea-surface temperature from 40°W to the western edge of the Gulf of Mexico was greater than 26.5°C. As can be seen in Figure 3, this appears to be a valid assumption. It appears to be particularly valid from July through September and this is when the overwhelming majority of the test matches occurred.

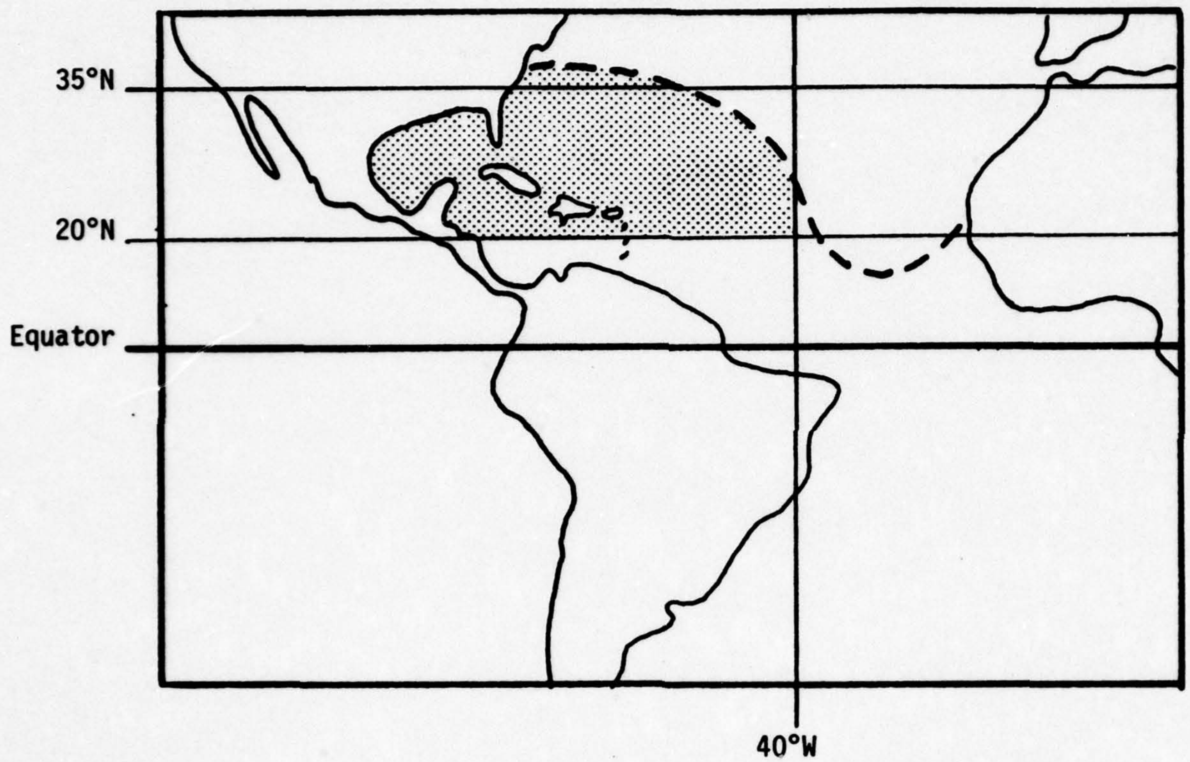

Fig. 3. Average 26.5°C sea-surface temperature isotherm for August. The dashed line indicates the isotherm position. Sea-surface temperatures south of the line to 20°N (stippled) average greater than or equal to 26.5°C. The 35°N line is provided as a reference position (from Gray, 1968).

5. RESULTS

a. Sample Cases

For the purpose of this study, the analog match could have resulted in one of the following: (1) a match which developed similarly to the actual depression, (2) a match that did not develop similarly, (3) a match that developed when the depression did not, (4) one that did not develop when the depression did not, or (5) the special case of the analog match already being at the tropical storm or hurricane intensity level for both the developed and non-developed depressions. Obviously, it would not be possible to show all of the sample cases, so only the extremes of the above categories will be shown. This is done in order to hold the number of figures within manageable limits. This section is being presented to give the reader a better appreciation of the testing procedures. The statistical significance of the results of all of the test cases will be presented in detail in the next section.

The optimum for this prediction scheme would be to have an analog match low center develop exactly as the test depression did. For all of the following examples, the 1200 GMT actual tropical depression position is indicated on each historical map with a ★ and the letters "TD" below it. On each subsequent chart, the ★ remains fixed as a reference position. The tropical depression which developed into hurricane Becky on August 9, 1974, was located at approximately 33°N, 68.5°W on August 28. The 1200 GMT analog match bulletin for that date indicated that the September 10, 1963, historical map was correlated at 0.8223 in the 40° to 130°W section. When this analog map was examined, a similar depression was located at approximately 32°N, 65°W or about 180 n mi from the actual depression center (Fig. 4). The next two days of historical maps are shown in Figure 5 and Figure 6. On the day when Becky had developed into a hurricane, the analog match had developed into a tropical storm. This case was chosen because it had one of the highest correlation coefficients along with a close proximity of the analog low center to the depression position. Other cases gave as many as three days of notification that development would occur.

The next case to be considered is when the analog match should have developed but did not. Such a case occurred with the tropical depression that became hurricane Candice off the east coast of the United States on August 19, 1976. This depression was located about 31.5°N, 69°W on August 18. The analog match bulletin for this date indicated a correlation coefficient of 0.7942 for the 1200 GMT July 28, 1955, historical map (Fig. 7). As can be seen, a similar analog low center was located approximately 60 n mi from the actual depression center, but no subsequent development took place in the analog series - thus giving a poor forecast (Fig. 8 and Fig. 9).

For this scheme to be considered acceptable, it must not over-forecast development, i.e., forecast the development of a tropical depression that in fact did not develop. The tropical depression that was located at 21.5°N, 97°W on September 7, 1975, dissipated on September 10. However, the analog bulletin for September 7 indicated

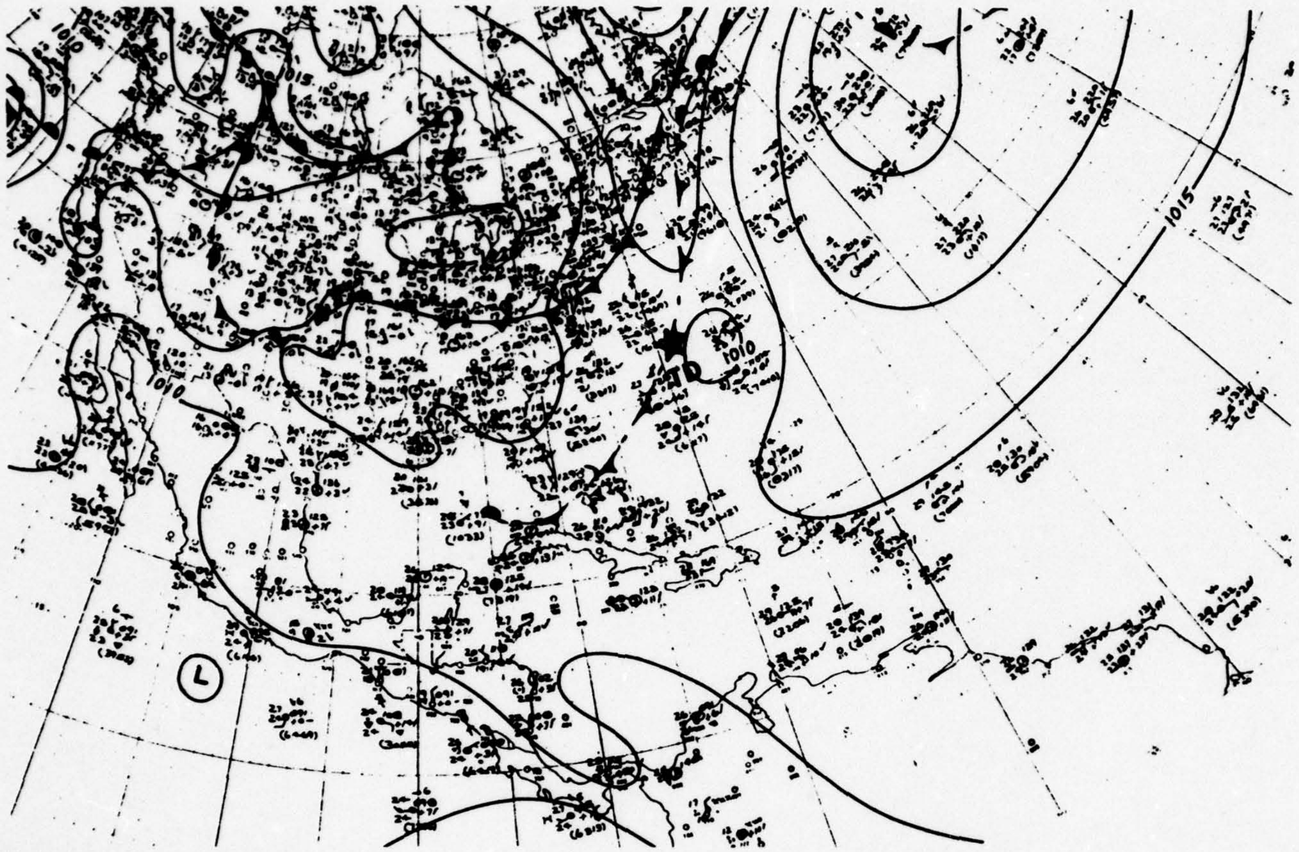

Fig. 4. Historical synoptic map section for 1200 GMT on September 10, 1963. The ★ remains fixed as a reference position.

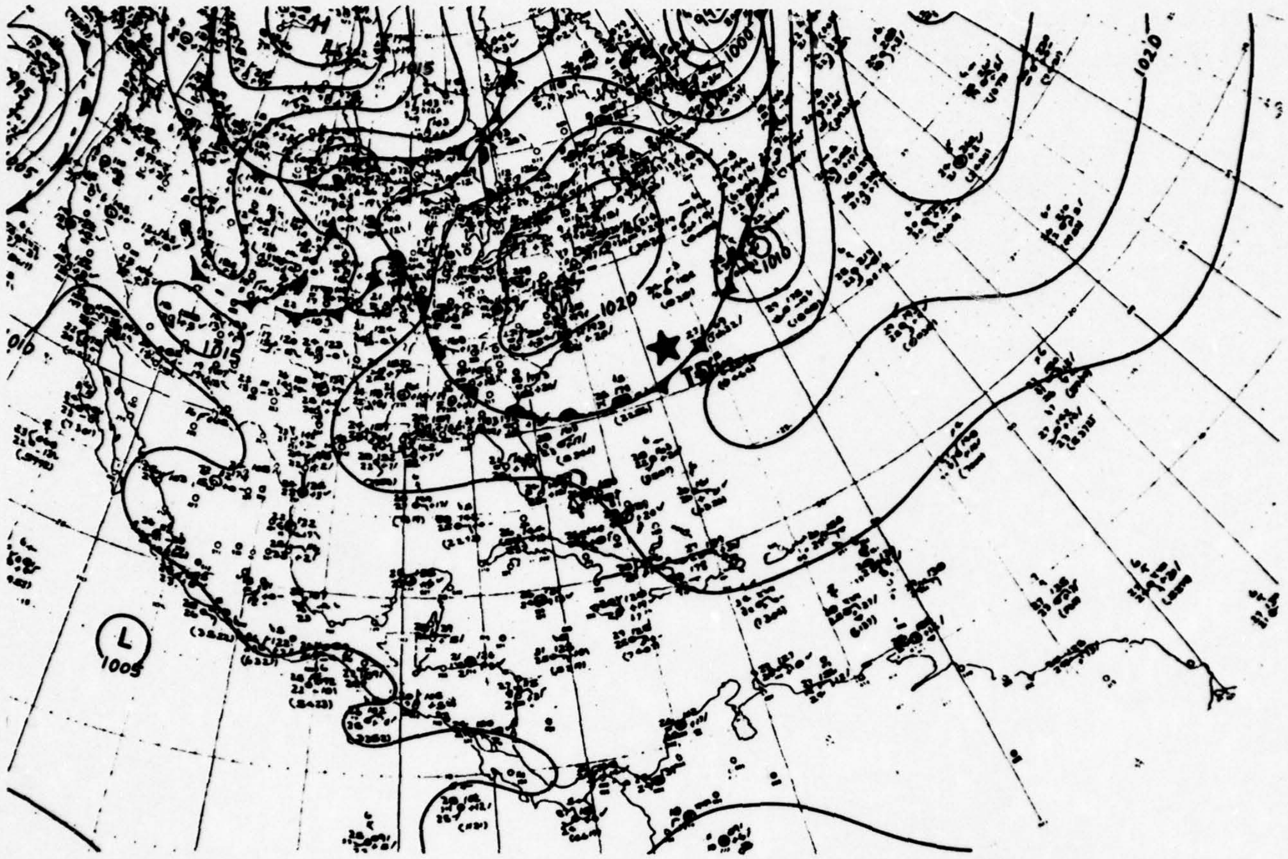

Fig. 5. Historical synoptic map section for 1200 GMT on September 11, 1963. The ★ remains fixed as a reference position.

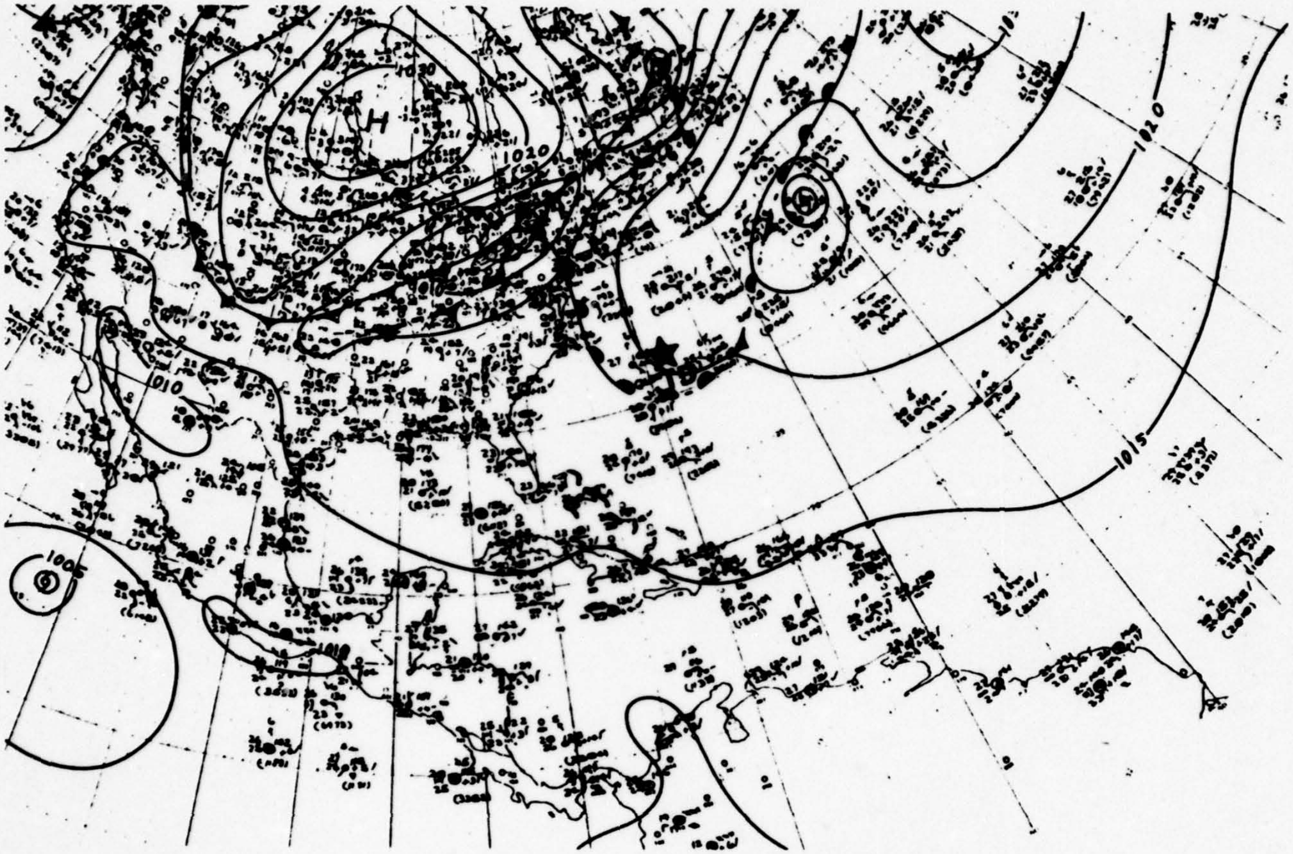

Fig. 6. Historical synoptic map section for 1200 GMT on September 12, 1963. The ★ remains fixed as a reference position.

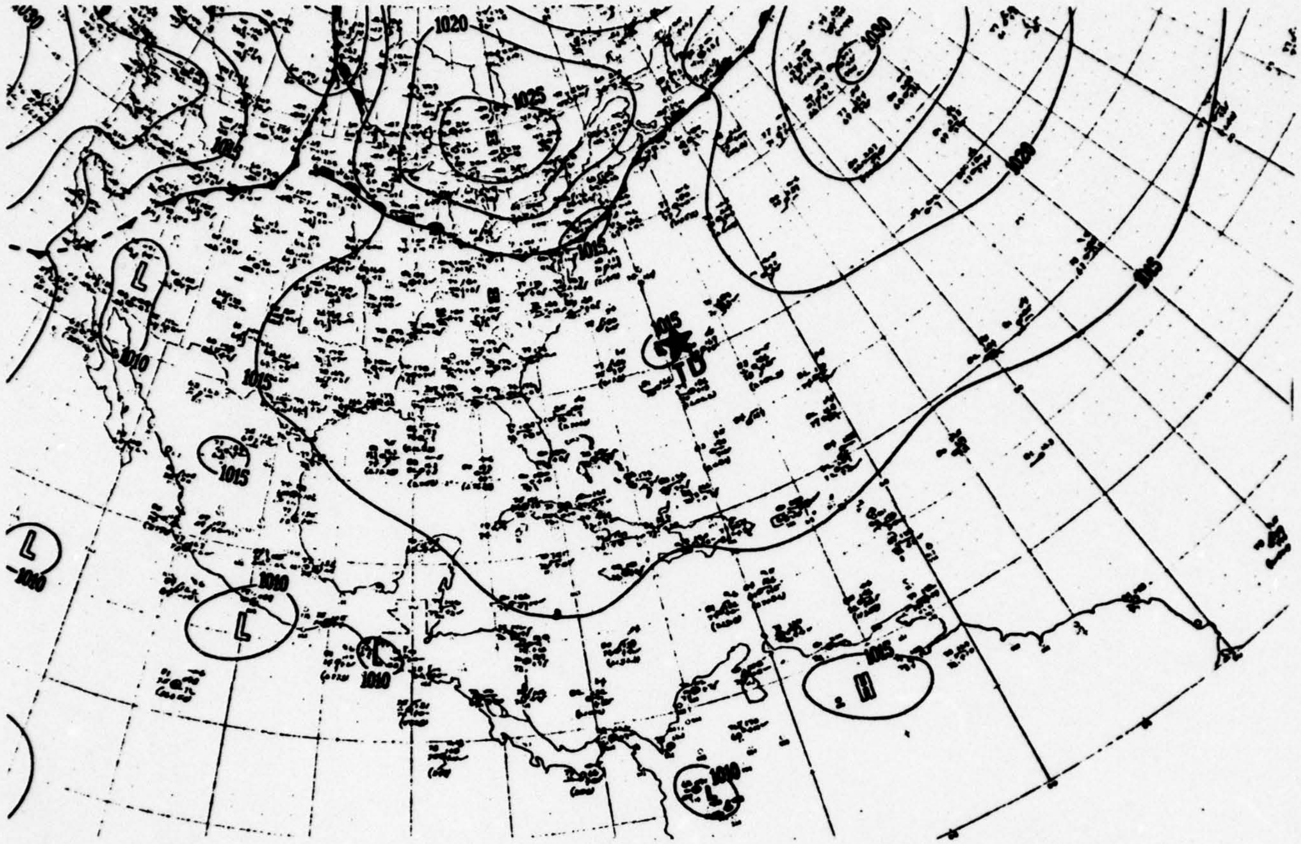

Fig. 7. Historical synoptic map section for 1200 GMT on July 28, 1955. The ★ remains fixed as a reference position.

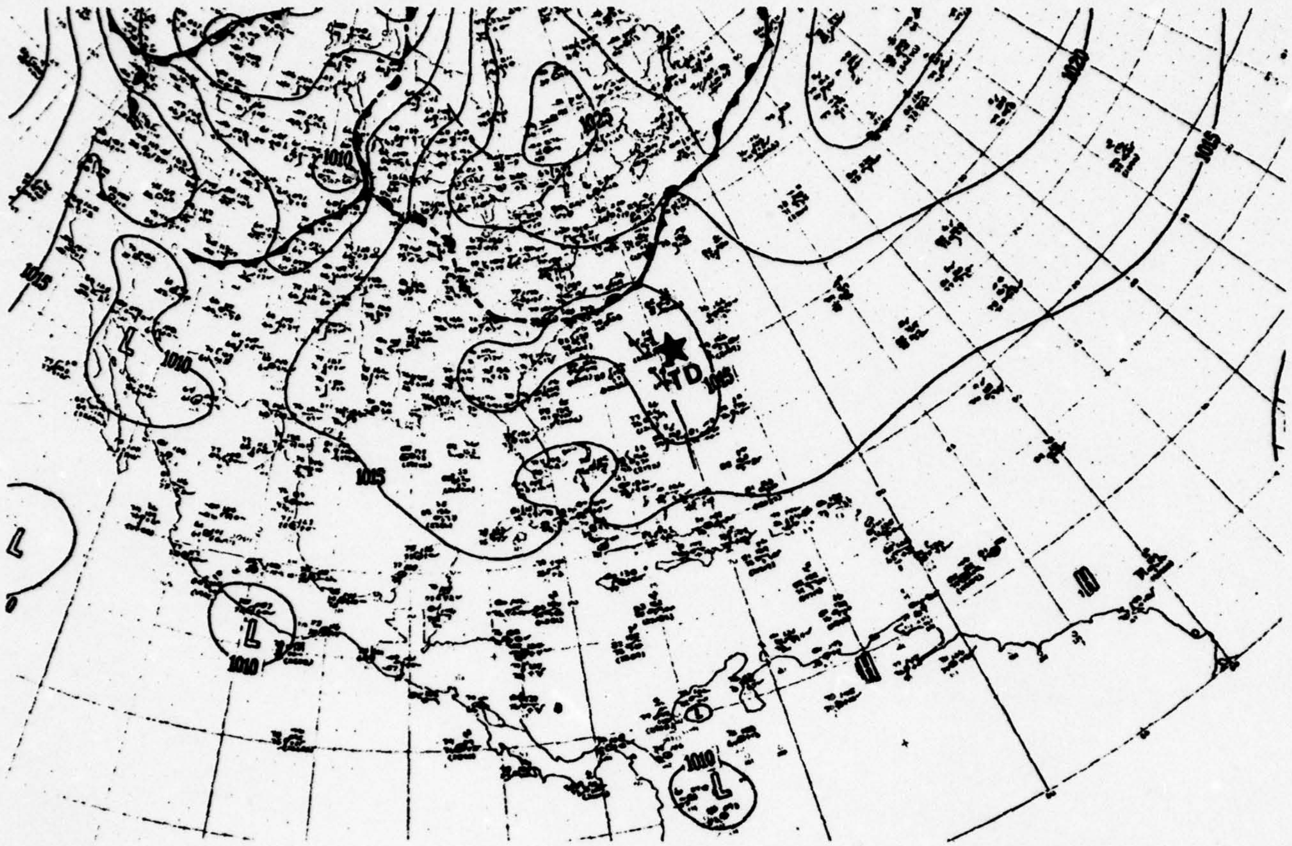

Fig. 8. Historical synoptic map section for 1200 GMT on July 29, 1955. The ★ remains fixed as a reference position.

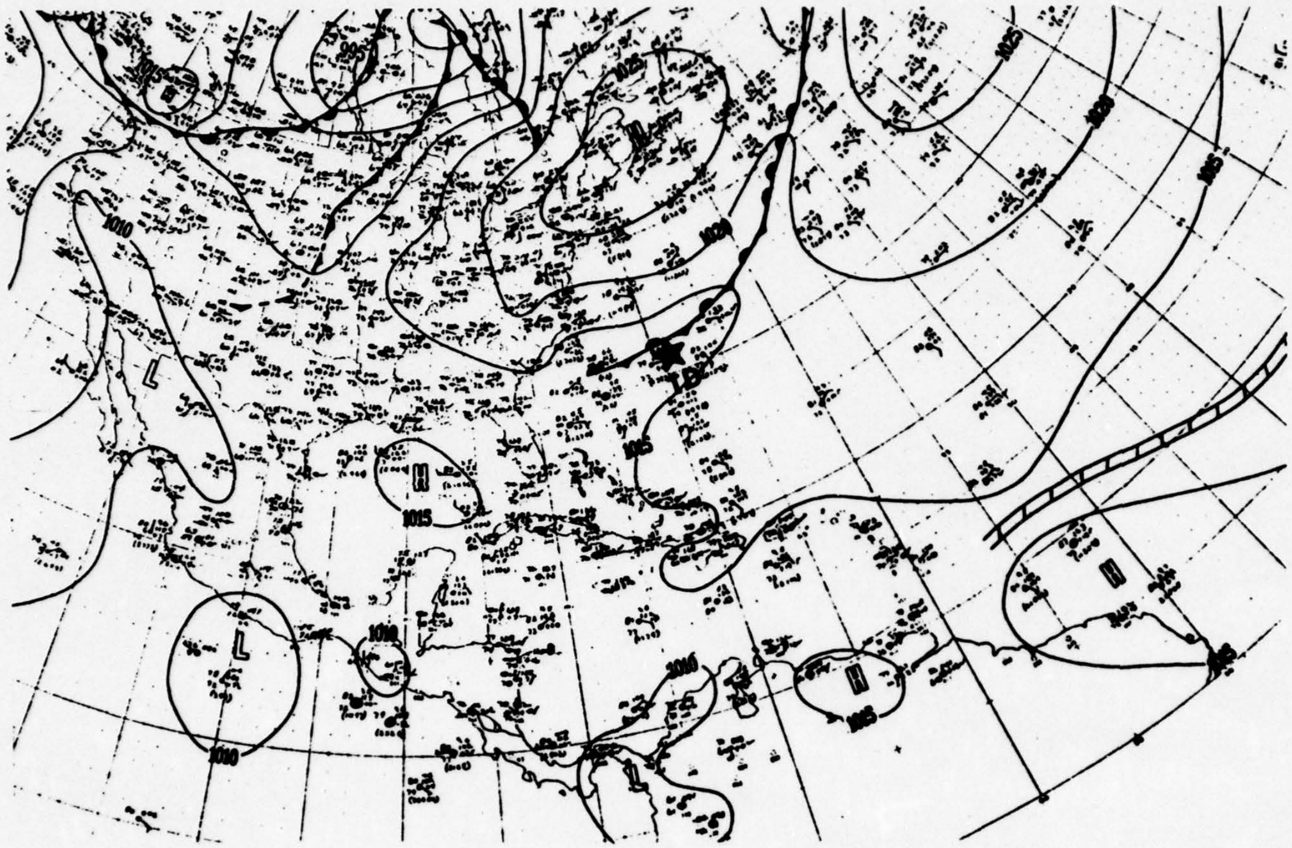

Fig. 9. Historical synoptic map section for 1200 GMT on July 30, 1955. The ★ remains fixed as a reference position.

that the September 2, 1955, historical map was correlated at 0.8827 and a similar low center was found approximately 120 n mi from the actual depression (Fig. 10). The analog match low center developed into a tropical storm three days later on September 10, 1955 (Fig. 11, Fig. 12, and Fig. 13), when this tentatively adopted forecast scheme indicated that it should have dissipated.

Examples are not shown when neither the depression nor its analog did not develop. In these cases, the analog low center moved inland, or more commonly dissipated. Neither are examples presented for the special cases where the analog match is already a hurricane or tropical storm, although, as was pointed out earlier, these cases became part of the data set. This will be elaborated on in the next section.

b. Statistical Significance

The data in this section are presented in two parts. The first part includes all analog matches with both the Department of Commerce Northern Hemispheric and Venezuelan historical maps used and, the second part, in which the Venezuelan map analog matches have been removed from the data set. This is being done to provide evidence of the problems that can be encountered when a non-homogenious set of historical maps is used in a synoptic analog forecasting technique and to provide a comparison to the verification results of this forecasting scheme.

As was pointed out earlier, a total of 51 actual tropical depressions remained after the data screens had been applied. Of these, 16 developed into at least tropical storms, the remaining 35 did not. A

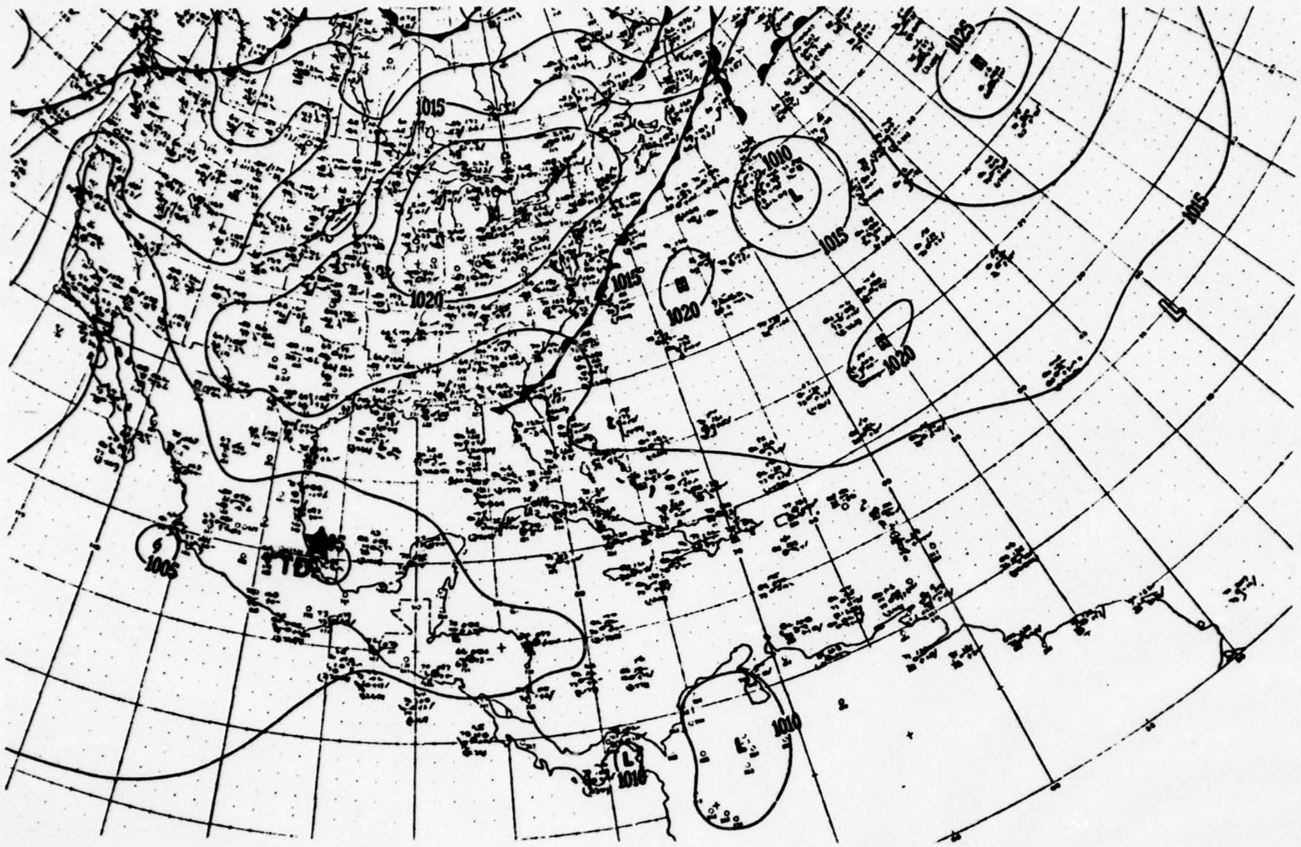

Fig. 10. Historical synoptic map section for 1200 GMT on September 2, 1955. The ★ remains fixed as a reference position.

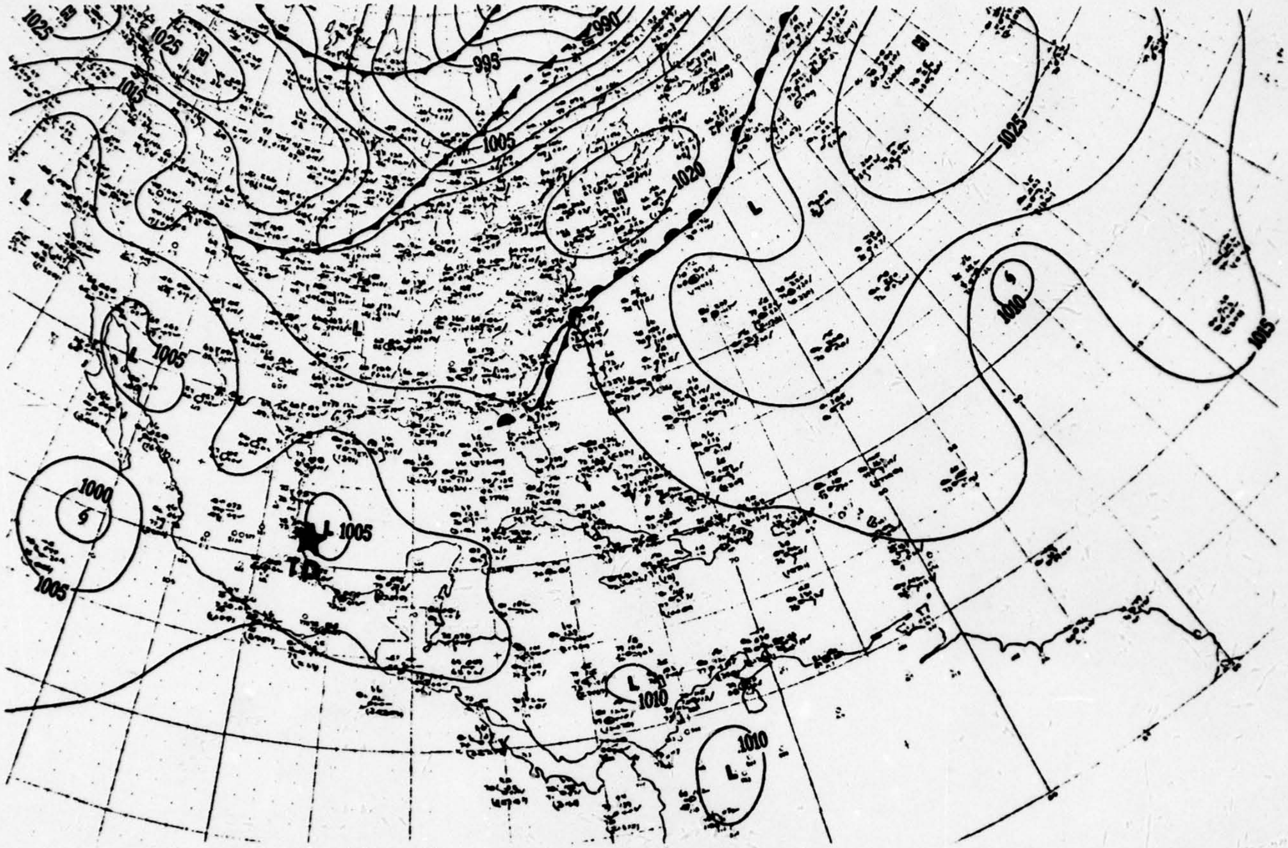

Fig. 11. Historical synoptic map section for 1200 GMT on September 3, 1955. The ★ remains fixed as a reference position.

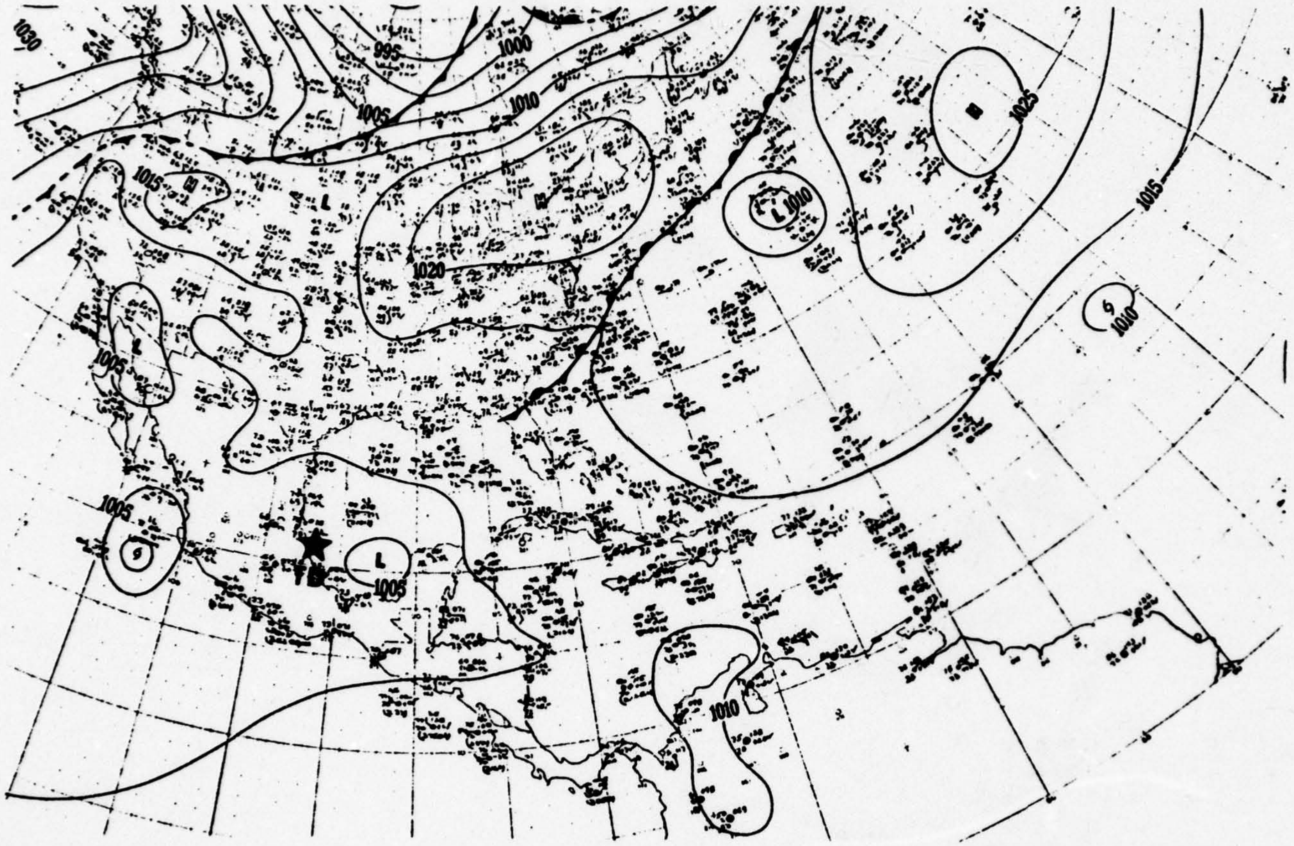

Fig. 12. Historical synoptic map section for 1200 GMT on September 4, 1955. The ★ remains fixed as a reference position.

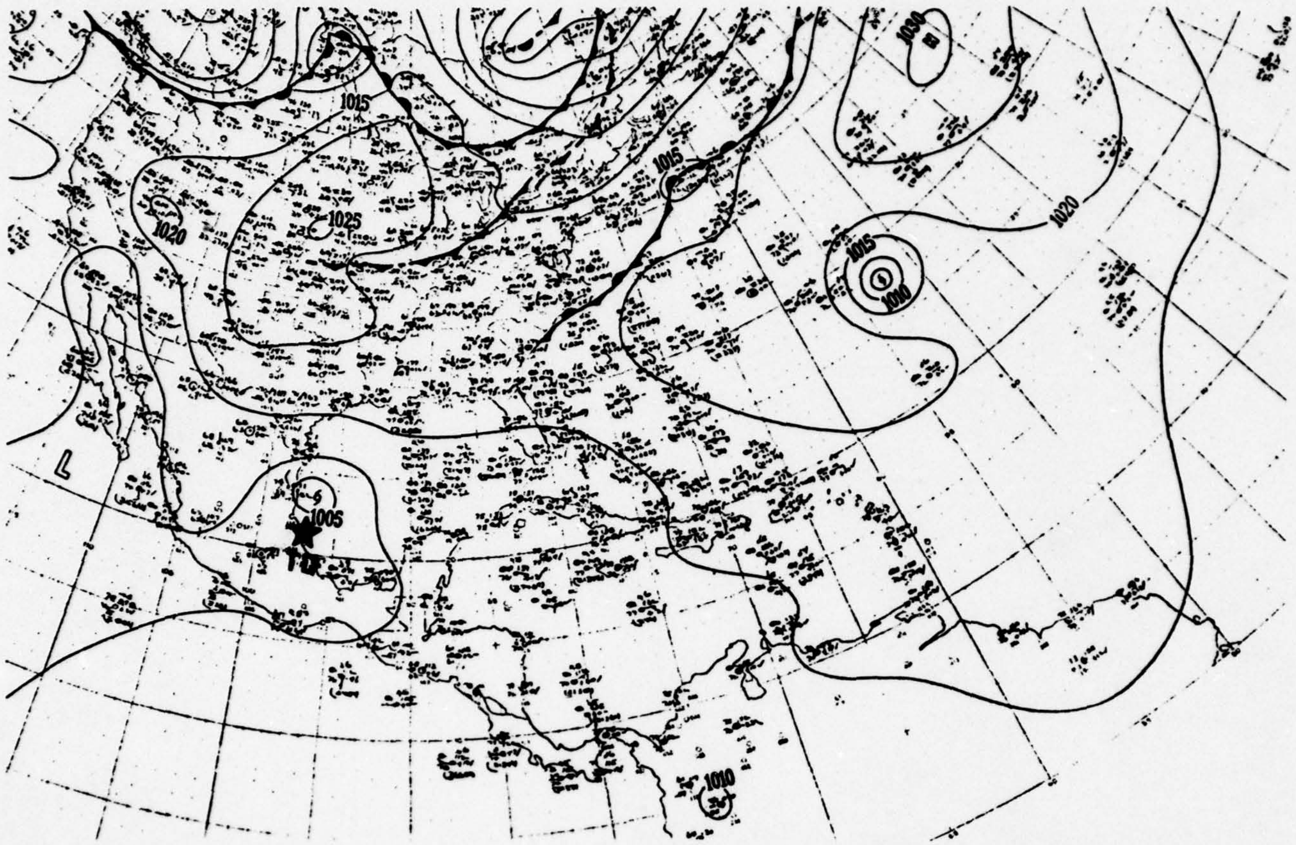

Fig. 13. Historical synoptic map section for 1200 GMT on September 5, 1955. The ★ remains fixed as a reference position.

total of 90 analog matches were found that met all the criteria for a successful match. Of these, 11 were eliminated because they were found on sequential days in the matching process and would tend to bias the sample. That is, if analog match low centers were found on historical maps with consecutive dates, only the match with the highest correlation coefficient was retained. Also, as was mentioned earlier, if the analog match was a tropical storm or hurricane, it was included. This was done because the scheme is to predict development and the presence of the storm indicates that development had or was taking place. This occurred in seven cases where the analog match low center was not supposed to develop and four cases where it was to develop. The breakdown of the analog match cases with the year in which they occurred is shown in Table 2. As can be seen from the table, the 16 depressions that did develop produced 25 analog matches; of these, 14 developed and 11 did not. Likewise, the 35 that did not develop produced 54 analog matches; of these, 12 developed and 42 did not.

Table 2. Non-developed and developed depressions' analog matches.

	Non-developed Match developed		Developed Match developed		
Year	Yes	No	Yes	No	Sub-total
1977	1	1	3	3	8
1976	3	15	1	2	21
1975	5	7	3	1	16
1974	3	19	7	5	34
Total	12	42	14	11	79

For all of the statistical tests applied to the data, the "null hypothesis" used will be that any analog match distribution was obtained purely by chance from the actual tropical depression distribution. A 5% criterion will be used for the rejection of the null hypothesis. That is, if any test gives a result of less than 5%, the probability that the analog matches were obtained by chance will be rejected.

The first test to be applied to the analog match data was the "chi-square", χ^2, and is presented by Brooks and Carruthers (1953) as

$$\chi^2 = \sum (d^2/E), \tag{1}$$

where E is the expected number of occurrences from a "no skill" table and d is the absolute difference between the expected and observed numbers. However, since the number of analog match cases (79) is larger than the number of actual depression cases (64), an apportionment process was employed to make the case numbers equal. This would seem to be a statistically safe procedure as the main interest is in the ratio of developed to non-developed analog cases, rather than their absolute number. For example, the 16 cases which did develop from analog matches of actual depression that themselves had developed becomes

$$(16/25) \times 14 = 8.96. \tag{2}$$

The complete observational table is presented in Table 3. Note that even though the table deals with fractional occurrences the total number of occurrences is 51, the original number of depressions being investigated. Numbers in parentheses are the non-apportioned numbers.

Table 3. Analog match observational table.

	Developed	Non-developed	Total
Developed	(14) 8.96	(11) 7.04	16
Non-developed	(12) 7.78	(42) 27.22	35
Total	16.74	34.26	51

The corresponding position in a "no skill" table is given by the product of the probability of reaching that box, divided by the total number of forecasts (Panofsky and Brier, 1958). For example, again for the developed analog match from the developed depression, that value becomes

$$(16 \times 16.74)/51 = 5.25. \qquad (3)$$

The completed "no skill" table is given in Table 4.

Table 4. Analog match "no skill" table.

	Developed	Non-developed	Total
Developed	5.25	10.75	16
Non-developed	11.48	23.51	35
Total	16.74	34.26	51

Before preceding to the calculation of χ^2, one further correction needs to be applied. According to Panofsky and Brier (1958), a correction devised by F. Yates is desirable whenever the population from which the expected number of occurrences is small. This correction involves reducing each value of the absolute discrepancy (d) by 0.5 prior to squaring. This value is presented in the last column of Table 5. In the table, O represents the observed number of analog matches from Table 3, and E the expected number from Table 4.

Table 5. χ^2 computational data.

O	E	d	$\frac{(d-0.5)^2}{E}$
8.96	5.25	3.71	1.96
7.78	11.49	3.71	0.90
7.04	10.75	3.71	0.96
27.22	23.51	3.71	0.44

Entering the values in Table 5 into Eq. (1),

$$\chi^2 = 4.26. \qquad (4)$$

The number of restrictions encountered in determining the "number of degrees of freedom" is one. That was caused by the number of individuals in the hypothetical distribution not being the same as that in the sample distribution. For this example, n = 2-1 = 1. From a limiting value of χ^2 table, and with one degree of freedom, a value of 4.26 is between the 5.02 at 2.5% and 3.84 at 5%. Therefore, a departure of observed from expected this extreme, or more extreme, could occur by chance with a probability of between 2.5 and 5%.

The next test applied to the data in Table 3 was the tetrachoric correlation (Brooks and Carruthers, 1953) which can be used in the case where both variables are divided into only two classes. If two related variates X and Y, which are known to be normally distributed, are arranged in a two-by-two classification with cell frequencies a, b, c, and d as follows

	$Y > Y_o$	$Y < Y_o$
$X > X_o$	a	b
$X < X_o$	c	d

then an approximation to the correlation coefficient between them is given by

$$r_t = \sin\left[\frac{\Pi}{2}\ \frac{(ad)^{\frac{1}{2}} - (bc)^{\frac{1}{2}}}{(ad)^{\frac{1}{2}} + (bc)^{\frac{1}{2}}}\right] . \tag{5}$$

Entering the corresponding values from Table 3 into Eq. (5) gives

$$r_t = \sin\left(90\ \frac{15.62 - 7.40}{15.62 + 7.40}\right) = \sin 32.14° = 0.532. \tag{6}$$

When testing for significance, the true value of r_t is assumed to be zero, and in such a case the standard error is

$$\text{S.E.}(r_t) \approx \frac{1}{z_h\ z_k\ (N)^{\frac{1}{2}}}\left(\frac{(a+b)(a+c)(d+b)(d+c)}{N^4}\right)^{\frac{1}{2}} , \tag{7}$$

where N is the total number of cases in the sample and z_h and z_k are the ordinates which cut the normal distribution at the points (a+b)/N and (a+c)/N. These values are taken from a normal frequency distribution table. Inserting the appropriate values into Eq. (7), the standard error is

$$S.E.(r_t) = \frac{1}{(0.361)(0.353)(7.14)} \left(\frac{(16)(16.74)(34.26)(35)}{51^4} \right)^{\frac{1}{2}} = 0.239. \quad (8)$$

Thus, 2 S.E.(r_t) is 0.478, and (just as with the χ^2 test) the result is significant at less than 5%.

The results of both the tetrachoric correlation and the χ^2 test suggest that the analog match distribution might not have occurred by chance from the actual tropical depression distribution. Next, it was decided to test the individual distributions of the developed and non-developed analog matches against their respective actual depression distributions. Recall that, of the 51 actual tropical depressions, 31.4% (16) developed into tropical storms or hurricanes and 68.6% (35) did not develop. From the data in Table 2, of the 54 analog matches for the non-developed depressions, 42 did not develop and 12 did. Similarly, for the developed depressions, 11 did not develop and 14 did. The binomial theorem (Brooks and Carruthers, 1953) was chosen to determine what the probability is of finding 42 or more non-developed analog matches in 54 attempts with the actual probabilities being 0.686 and 0.314. Also, what is the probability of finding 14 or more developed analog matches in 25 attempts?

Since the probabilities p and q of development and non-development are not equal, the distribution becomes skew. The probability of a given occurrence is determined by the appropriate element of the series shown in Table 6. For the non-development cases, n = 54, p = 0.314, and q = 0.686. After calculation of the series in Table 6, the probability of getting 47 or more non-developed analog matches in 54 attempts is 0.092. Therefore, the binomial test indicates, at the 5% significance level, that the analog non-development matches could have been obtained by chance.

Table 6. Binomial theorem series.

Number of Occurrences	Probability of Occurrences
0	q^n
1	npq^{n-1}
2	$\frac{n(n-1)}{2!} p^2 q^{n-2}$
3	$\frac{n(n-1)(n-2)}{3!} p^3 q^{n-3}$
.	.
.	.
.	.
.	.
n	p^n

The development analog match cases, however, indicated more promise. For these matches, n = 25, q = 0.314, and p = 0.686. After the calculation of the series in Table 6, the probability of getting 14 or more developed analog matches in 25 attempts was 0.009. Therefore, for the developed analog matches, the null hypothesis is rejected and it is assumed (with a less than 1% chance of error) that these developed analog matches would not be obtained by chance from the actual tropical depression distribution.

The final statistical device applied to the analog match cases was to compute a skill score (S). The form used was that presented by Panofsky and Brier (1958) as

$$S = \frac{R - E}{T - E} , \qquad (9)$$

where R is the number of correct forecasts, T is the total number of forecasts, and E is the number expected to be correct based on chance. Entering the corresponding values from Table 3 and Table 4 into Eq. (9) gives a skill score of

$$S = \frac{36.18 - 28.76}{51 - 28.76} = 0.334. \qquad (10)$$

This score has a value of unity when all forecasts are correct and has a value of zero when the number correct is equal to the expected number correct. Therefore, it can be stated that the technique exhibits some "skill", but the extent of that "skill" cannot be determined as no suitable comparison skill score is available. Normally, the comparison skill score is based on either persistence or climatology, but since the actual data is based partly on climatology and persistence, such a comparison has no meaning in this case. Thus, an alternative method had to be found to determine what skill is exhibited.

Since some skill is exhibited by the tentative forecast scheme and, statistically, the developed analog matches probably were not obtained by chance, the developed analog match data were analyzed further to determine the number of times the scheme correctly predicted the actual tropical depression's development. To do this, the following criteria were used to determine which developed analog matches were utilized for verification purposes: (1) only the match with the highest correlation coefficient, (2) only the closest analog low center to the depression's position, (3) an arbitrarily weighted correlation coefficient (CC2) between the actual correlation coefficient (CC) and the distance such that

$$CC2 = CC - \frac{X}{480} CC , \tag{11}$$

where X is the distance (in 60 n mi increments) between the analog match and the actual depression position, and (4) the maximum number of correct or incorrect matches on each bulletin for the 40 analog candidates. Since this is a prediction scheme, all ties in categories (2) and (4) were considered correct forecasts. The results of the analyses on the remaining 11 tropical depressions are shown in Table 7.

Table 7. Developed analog match analysis.

	Correctly forecast	
	Yes	No
Highest correlation	3	5
Nearest match	5	3
Weighted correlation	3	5
Maximum number of matches	4	4

The results indicated in Table 7 were somewhat surprising in view of the statistical evidence that the development cases probably were not obtained by chance and indicated skill in prediction. Consequently, a re-analysis of the basic procedures was undertaken. The most likely cause of these disparate results was found to be the inclusion of the Venezuelan data into the basic scheme. It was determined that the Venezuelan analyses contained many more low centers than the Northern Hemispheric daily series because the Venezuelan analyses were done mainly for forecasting in the tropics rather than for historical reference. Consequently, the Venezuelan analyses were done in much finer detail than the Northern Hemispheric series and contained many smaller resolution low centers that should not have been equated to tropical depressions. It was decided, therefore, that an identical statistical analysis of the data should be done with these 1970 through 1976 analog matches excluded.

Recall from Table 2 that the total number of analog matches was 79. The corresponding analog matches without the Venezuelan data are shown in Table 8 with the number of Venezuelan matches removed in Table 9. Note the large number of non-development analog cases in Table 9 that occurred due to the Venezuelan data. It was assumed that this was due to the larger number of low centers on the Venezuelan analyses which were not low centers that could have developed into tropical storms or hurricanes.

As was done earlier with the data set that included the Venezuelan data, the apportioned data for the cases excluding the Venezuelan matches are shown in Table 10 and the corresponding "no skill" table

Table 8. Analog match cases excluding 1970 through 1976 Venezuelan matches.

Year	Non-developed Match developed Yes	No	Developed Match developed Yes	No	Sub-total
1977	1	0	1	2	4
1976	2	7	1	1	11
1975	4	3	3	1	11
1974	2	10	6	3	21
Total	9	20	11	7	45

Table 9. Venezuelan analog match cases (1970 through 1976).

Year	Non-developed Match developed Yes	No	Developed Match developed Yes	No	Sub-total
1977	0	1	2	1	4
1976	1	8	0	1	10
1975	1	4	0	0	5
1974	1	9	1	2	13
Total	3	22	3	4	32

Table 10. Apportioned analog match cases excluding 1970 through 1976 Venezuelan matches.

	Developed	Non-developed	Total
Developed	(11) 9.78	(7) 6.22	16
Non-developed	(9) 10.86	(20) 24.14	35
Total	20.64	30.36	51

is shown in Table 11. Similarly, the χ^2 computational data are shown in Table 12.

Table 11. Analog match "no skill" table excluding Venezuelan matches.

	Developed	Non-developed	Total
Developed	6.48	9.52	16
Non-developed	14.16	20.84	35
Total	20.64	30.36	51

Table 12. χ^2 computational data excluding Venezuelan matches.

O	E	d	$\frac{(d-0.5)^2}{E}$
9.78	6.48	3.30	1.21
10.86	14.16	3.30	0.55
6.22	9.52	3.30	0.82
24.14	20.84	3.30	0.38

Entering the values from Table 12 into Eq. (1),

$$\chi^2 = 2.96 \qquad (12)$$

From a limiting value of χ^2 table, a value of 2.96 is between 3.84 at 5% and 2.71 at 10%. Thus, the analog match distribution could have been obtained from the actual tropical depression distribution by chance.

Again, the next test to be applied to the data in Table 10 is the tetrachoric correlation. Entering the values into Eq. (2), the correlation coefficient is

$$r_t = \sin\left(90\,\frac{15.37 - 8.22}{15.37 + 8.22}\right) = \sin 27.28° = 0.458 \qquad (13)$$

From Eq. (3), the standard error is

$$S.E.(r_t) = \frac{1}{(0.361)(0.353)(7.14)}\left(\frac{(16)(20.64)(30.36)(35)}{51^4}\right)^{\frac{1}{2}} = 0.250 \qquad (14)$$

Thus, 2 S.E.(r_t) is 0.500 and the result of the test shows that, at the 5% significance level, the analog match distribution might have been obtained by chance from the actual tropical depression distribution.

The next test applied to the data was the binomial distribution test (see page 36). For the non-developed analog cases, n = 29, q = 0.686, and p = 0.314. After calculation of the series in Table 6, the probability of getting 20 or more non-developed analog matches in 29 attempts was 0.572. This indicates that there was no significant difference between the analog non-developed match distribution and the actual tropical depression distribution.

As happened before, however, the developed analog cases did have a probability of less than 5%. For these cases, n = 18, q = 0.314, and p = 0.686. After calculation of the series in Table 6, the probability of finding 11 or more developed analog matches in 18 attempts was 0.008, and was considered significantly different from the actual tropical depression distribution. Entering the appropriate values from Tables 10 and 11 into Eq. (4), the skill score was

$$S = \frac{33.92 - 27.32}{51 - 27.32} = 0.279. \qquad (15)$$

As mentioned before, the degree of skill cannot be determined, so a similar verification scheme as that used for Table 7 was computed for these data. The results of the verification are shown in Table 13 under the heading "Venezuelan excluded." The comparison data entitled "Venezuelan included" is repeated from Table 7.

Table 13. Comparison of analog match verification data.

	Venezuelan excluded Correctly forecast		Venezuelan included Correctly forecast	
	Yes	No	Yes	No
Highest correlation	4	4	3	5
Nearest match	6	2	5	3
Weighted correlation	5	3	3	5
Maximum number of matches	5	3	4	4

6. CONCLUSIONS

This study demonstrated that a synoptic analog forecasting scheme exhibits some skill in predicting the development of tropical depressions in the North Atlantic Ocean. The forecasting scheme would allow an objective input into an initial development forecast. However, the scheme is unwieldy because of the large number of maps which must be reviewed and the resultant amount of time that must be expended. A possible solution to this problem will be discussed in the recommendations section.

Secondly, this study indicated the pitfall of changing either the scale of the historical maps or the techniques used to analyze the synoptic data on those maps. It appears that any such study must make use of as uniform a historical map series as possible.

While the forecasting of tropical depression development appears valid, the converse does not. That is, a forecast scheme to predict which tropical depression will not develop does not appear feasible. Although a similar verification to that done on the developed analog matches would not be statistically significant for the non-developed cases, an identical analysis was done out of curiosity. In this analysis, all ties were considered as a non-development forecast. All catagories were between 53 and 65% correct, which is less than the 69% that would be expected only from a climatological forecast for this data set. It was, therefore, concluded that little or no skill was exhibited by the non-developed analog matches.

The final conclusions about the development cases deals with the data in the verification tables for both all cases and the cases with the Venezuelan data excluded. It is interesting to note that the highest verification was achieved when the nearest match on each bulletin was used for the forecast. However, the poorest verification occurred when the analog match with the highest correlation coefficient was used to forecast development. The highest correlation for any match was +0.9397 and the lowest was +0.5470. The average for all of the analog-developed matches was +0.7475. Since these values range from -1.000 to +1.000, it was concluded that, once the synoptic patterns had been reasonably well correlated, the relatively minor fluctuations in the degree of correlation were not crucial to the success of the forecasting scheme. A possible test of this conclusion will be elaborated on in the recommendations section.

7. RECOMMENDATIONS

The following recommendations for further study are presented:

1) That a similar study be done with a model that more precisely evaluates the correlation between the current synoptic patterns and historical weather patterns over an area from the west coast of Africa to the western edge of the Gulf of Mexico and from 40°N to the equator. It was felt during this study that, because of the extensive northern area in the North American block of the Navy analog model, the correlation of the weather patterns should be more confined to tropical regions.

2) That rather than using a synoptic historical map series, maps similar to the Monthly Weather Review tropical depression position maps be constructed to cover the period from 1946 to the present. This would insure that tropical depressions are being compared to other tropical depressions, would greatly facilitate the search for similar depressions, and significantly reduce the amount of time required for the search.

3) That an alternate method be devised to more accurately incorporate sea-surface temperatures into the forecast scheme. Average monthly sea-surface temperature charts might not be sufficient when peripheral development months, such as May, June, October, and November, must be forecast.

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APPENDIX A

THE NAVY ANALOG MODEL

Appendix A is provided for readers not familiar with the Navy automated long range (analog) forecast model. All information presented below is from McConathy and Thormeyer (1974). Those persons requiring greater detail are referred to McConathy and Thormeyer (1974) which contains, besides the model's specifications, information about the philosophy behind analog forecasting, the history of the model, and forecast verification statistics.

The historical map data bank consists of Northern Hemispheric surface and 500 mb analyses from 1946 to the present. Fleet Numerical Weather Central (FNWC) analyses have been used since 1962. To insure as much homogenity and continuity as possible from map to map, all of the non-FNWC analyses were re-analyzed in a manner approximating the current FNWC objective numerical analysis scheme. The data base is being continually updated by FNWC's Climatology Department.

In order to obtain the 40 analog match dates, all years in the historical data base are searched ± 30 days from the current calendar date for the following parameters: (1) the large scale disturbance field at 500 mb, (2) the large scale disturbance field at 1000 mb, (3) the 500 mb height field, and (4) the 1000 mb height field. Hemispheric correlations between the historical charts and the current charts are computed using all grid points north of 20°N (approximately 1500) according to Eq. (16).

$$r = \frac{\sum(x - \bar{x})(y - \bar{y})}{\left[\sum(x - \bar{x})^2 \cdot \sum(y - \bar{y})^2\right]^{\frac{1}{2}}} \tag{16}$$

where r is the correlation coefficient, and x and y are corresponding grid points on the current and historical data fields being correlated. This process yields approximately 1920 individual correlations for each of the four parameters. These correlations are then normalized using Eq. (17)

$$N = \frac{r - \bar{r}}{\sigma} \tag{17}$$

where r is the correlation value of a specific historical chart with the current data, $\bar{r}$ is the mean of all 1920 correlations for that parameter, and σ is the standard deviation of the 1920 correlations for that parameter. The normalized values for all four parameters from the same historical data are averaged yielding one correlation (N) for each date. The 1920 normalized and averaged correlations are then ranked, and the 40 best matches are selected for the analog bulletin.

VITA

David A. Grimm was born on April 1, 1943, in Chicago, Illinois to Mr. and Mrs. C. M. Grimm. After graduating from Calumet High School in 1961, he enlisted in the United States Air Force. He graduated from the Air Weather Service's weather observer and weather forecaster schools. He served as a weather observer from 1961 to 1968 and as an enlisted weather forecaster from 1969 to 1972.

While overseas in 1963, he began taking college courses through the Paris division of the University of Maryland and, during subsequent assignments in the United States, continued to attend night school until he had accrued sufficient college credits to be accepted into the Airman's Education and Commissioning Program in 1972. Through this program, he was sent to Texas A&M University and received his Bachelor of Science degree in meteorology in 1974. He was immediately sent to attend Officer's Training School and was commissioned a 2nd Lieutenant in August of 1974.

After commissioning, he was assigned to the Air Force Global Weather Central where he became the Officer in Charge of the Central's Medium Range Forecast Unit. He performed graduate work in the field of meteorology at Texas A&M from 1977 through 1978. Captain Grimm is currently assigned as a technical consultant to the Space and Missile Systems Organization at the Los Angeles Air Force Station, California. His permanent mailing address is 111 Alfred Drive, Vicksburg, Mississippi.

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