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A STATISTICAL TROPICAL CYCLONE MOTION FORECASTING SYSTEM FOR THE GULF OF MEXICO

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ABSTRACT. The development of a statistical (climatology and persistence) model for the prediction of tropical cyclone motion over the southwestern Gulf of Mexico is described. The system complements an existing statistical model (CLIPER - CLImatology and PERsistence), which is currently in operation at the National Hurricane Center but which does not perform well over this region of the Gulf.

Because of the small size of the region and the high dissipation rate of cyclones making landfall in Mexico, problems relating to the changing statistical properties of the developmental data arise. Three different sets of developmental data and their advantages and disadvantages are discussed.

The final operational version of this system is based on a data set in which the tracks of tropical cyclones dissipating within 36-72 h are linearly extrapolated to overcome a bias against forecasts of westward motion present in CLIPER. The study concludes with examples of forecasts produced by the system.

1. INTRODUCTION

Despite the introduction of more sophisticated techniques, tropical cyclone motion prediction models based only on climatology and persistence are still widely used in the world's tropical cyclone basins. Particularly at short time periods of 36 h and less, persistence and climatology account for a large percentage of the total variance explained by any statistical tropical cyclone forecast model (Neumann and Lawrence 1975; Neumann and Hope 1972). Climatology and persistence models are of two main types--analog and statistical. Analog models scan a data file containing all known tracks of tropical cyclones in a given basin, selecting as analogs those with motion, location, and date of occurrence similar to that of the cyclone to be forecast. These analogs are then combined to produce the forecast track.

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Statistical models consist of pairs of regression equations for prediction of zonal and meridional displacements of the cyclone center for forecast intervals 12 through 72 h in 12-h increments. The first statistical climatology and persistence model, CLIPER (CLImatology-PERsistence), became operational in the Atlantic basin in 1972 (Neumann 1972). CLIPER predicts zonal and meridional displacements at 12-h intervals through 72 h, using as predictors the day number, latitude, longitude, current meridional and zonal motion, meridional and zonal motion 12 h before forecast time and maximum wind of the cyclone. Similar CLIPER-type models have been developed for the eastern North Pacific Ocean (Neumann and Leftwich 1977), the southwest Indian Ocean (Neumann and Randrianarison 1976), and the north Indian Ocean (Neumann and Mandal 1978).

Although CLIPER equals or outperforms synoptic and dynamic models at short ranges and at southern latitudes within the Atlantic basin, seven seasons of operational use have revealed some deficiencies as well. CLIPER forecasts for tropical cyclones in the Gulf of Mexico, especially those with initial motion to the west or northwest, tend to curve sharply to the right, giving the model a bias to the north. The work presented in this paper is a result of efforts to reduce or eliminate this bias and increase forecaster confidence in the model over the Gulf of Mexico.

The immediate cause of the bias is apparent from the map of mean tropical cyclone motion vectors in Figure 1. Over the large area of the Atlantic basin northwest of the dashed line, the mean motion vectors show a gradual veering from the northwest through northeast with increasing latitude. The "typical" track in this area is a broad parabola described as the cyclones recurve around the edge of the subtropical ridge into the westerlies. Southwest of the dashed line, in the southwest Gulf of Mexico and northwest Caribbean Sea, cyclone motion is best approximated by a straight line or even a slightly leftward-curving one, especially during July and August.

One solution to this bias against westward-moving forecast tracks in CLIPER is to redevelop the regression equations using a data set incorporating only those cases located in a region of straight or left-curving mean tracks. Unfortunately, the sample size available for the longer-range prediction equations decreases sharply as the cyclones move inland and dissipate. This dissipation is not random but, rather, is most likely for westward-moving cyclones carried into the mountains of Mexico. Cyclones with a more northerly track into the United States are usually carefully tracked and may persist for days over the relatively smooth terrain. This paper describes possible methods to compensate for this bias by manipulation of the developmental data. Three sets of developmental data and the performance characteristics of the resulting forecast equations presented are discussed.

2. DEVELOPMENTAL DATA CONSIDERATIONS

Three developmental data sets were considered for use in developing the CLIPER-GULF motion prediction equations for the western Gulf of Mexico. To obtain the stratification desired, all cases to the northeast of the dashed

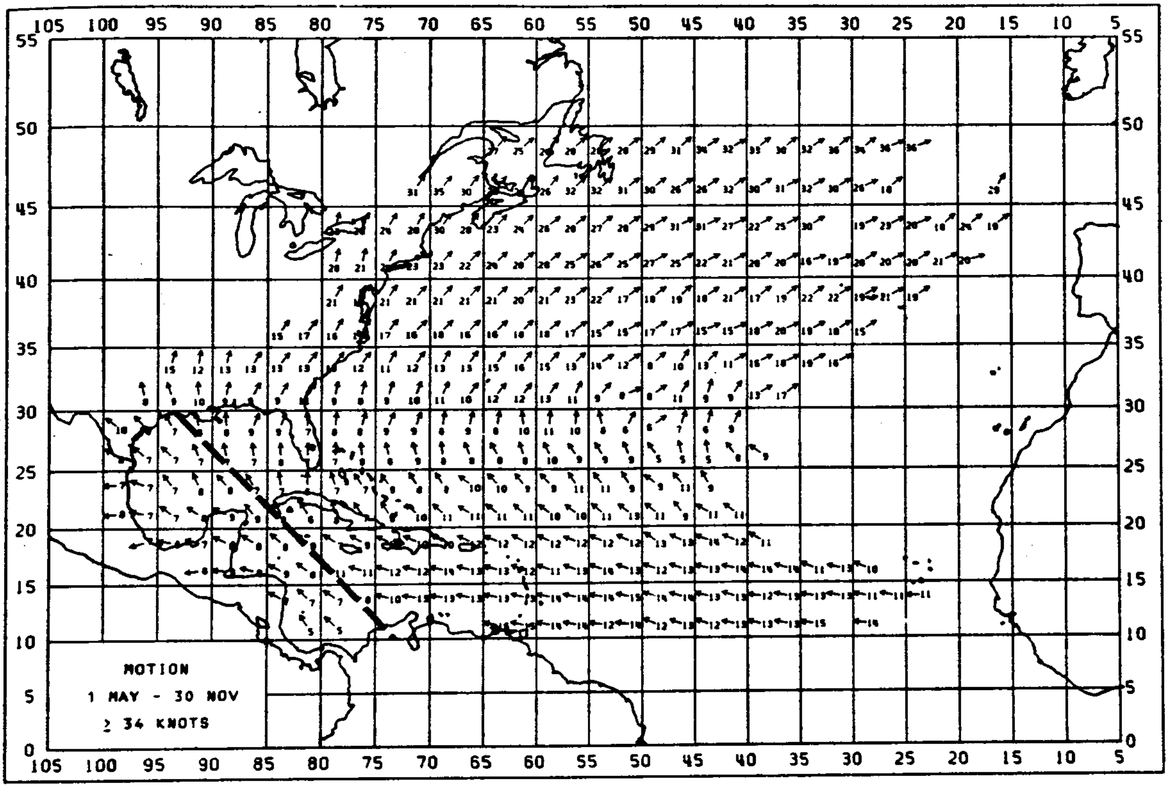

Figure 1. Mean motion vectors (resultant speeds and directions) for the period 1 May through 30 November for tropical cyclones with winds greater than 34 knots. The dashed line is the boundary of the CLIPER-GULF stratification region.

line in Figure 1 were immediately rejected. The different developmental data sets were then specified as subsets of this restricted set of cases from 1886-1979. In addition, 10 storms, selected at random, were removed for use as independent data. The homogeneous (HOM) data set uses only those cases for which at least 72 h of future displacements exist. Because motion 12 h before forecast time is included as a predictor in CLIPER and was to be included in CLIPER-GULF as well, any tropical cyclone with less than 84 h (3 1/2 days) of best-track positions is automatically excluded, as are cases in which dissipation occurs within 72 h. The non-homogeneous (NHOM) data set uses all available cases at each prediction time, 12 through 72 h. In this set (made up of 6 subsets, corresponding to the 6 forecast times), the number of cases and the statistical attributes of the predictors and predictands change with increasing forecast time. The third data set, extrapolated non-homogeneous (ENH), consists of the NHOM set for the 12, 24 and 36 h forecast equations, with linearly extrapolated displacements through 72 h for cyclones which persist longer than 36 but less than 72 h. These three developmental data sets are discussed in more detail below.

A. Homogeneous Data Set

The characteristics of the homogeneous (HOM) data set are shown in Table 1. A homogeneous data set is used in CLIPER and in the statistical climatology-persistence model for the southwest Indian Ocean (Neumann and Randrianarison 1976). The advantages of using a homogeneous data set are: (1) the sample means and standard deviations are constant for all predictor and predictands, resulting in smooth and "reasonable" forecast tracks, and (2) the constant statistical properties of the developmental data render the regression and screening process more efficient since the covariance matrix need only be computed once. The main disadvantage of the HOM data set is an inherent bias towards the longer duration tropical cyclones. This bias becomes critical over a small, landlocked area such as the Gulf of Mexico because of the high number of dissipating cases and short tracks. The sample size for the HOM data set is reduced by about 40 percent when the 72 h displacement restriction is imposed. Cyclones most likely to be included in the sample are those moving slowly or on a northerly course and failing to strike the mountains of Mexico where dissipation is rapid and almost certain. Figure 2 shows the total dissipation for 2.5 degrees latitude-longitude areas over the Gulf of Mexico region from best-track data, 1886-1979.

Table 1. Characteristics of the homogeneous (HOM) developmental data set for the CLIPER-GULF stratification region. All velocities and displacements are given in kt and nmi respectively, with north and east considered positive.

QUANTITY	SYMBOL	MEAN	STD. DEVIATION
Day Number	P1	249.1	46.4
Initial Latitude	P2	20.3	4.3
Initial Longitude	P3	87.2	4.9
Current Meridional Speed	P4	4.6	3.5
Current Zonal Speed	P5	-3.5	4.6
12 h Past Meridional Speed	P6	4.2	3.4
12 h Past Zonal Speed	P7	-4.2	4.6
Maximum Wind	P36	57.3	23.7
12 h Meridional Displacement	DY12	56.7	42.5
24 h Meridional Displacement	DY24	117.3	83.1
36 h Meridional Displacement	DY36	181.3	122.9
48 h Meridional Displacement	DY48	248.2	162.4
60 h Meridional Displacement	DY60	318.0	202.8
72 h Meridional Displacement	DY72	391.0	247.0
12 h Zonal Displacement	DX12	-36.4	55.9
24 h Zonal Displacement	DX24	-62.1	113.1
36 h Zonal Displacement	DX36	-76.5	173.4
48 h Zonal Displacement	DX48	-80.0	238.7
60 h Zonal Displacement	DX60	-71.9	309.0
72 h Zonal Displacement	DX72	-53.5	386.5
Number of Cases	N	1797	

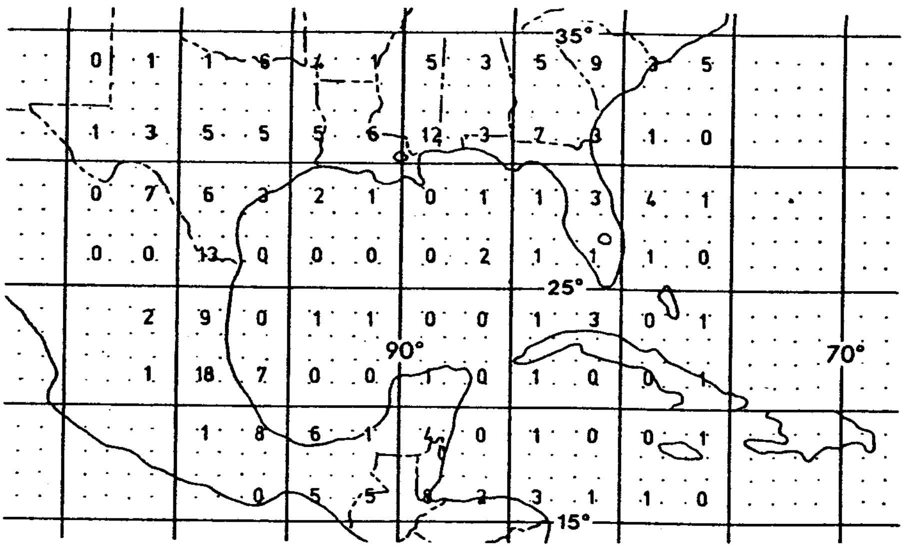

Figure 2. Number of tropical cyclone dissipations or best-track endpoints per 2.5 degree latitude-longitude regions for the period 1886-1979.

B. Non-Homogeneous Data Set

The characteristics of the non-homogeneous (NHOM) data set are given in Table 2. As stated earlier, this set is actually 6 sets, each composed of cases with displacements through the corresponding forecast time, 12-72 h. Non-homogeneous data sets are used for CLIPER-type systems for the eastern North Pacific (Neumann and Leftwich 1977) and north Indian Ocean (Neumann and Mandal 1978) tropical cyclone basins. Note that, with increasing forecast time, the mean motion becomes slower and more northerly and the mean initial location shifts southeastward. The primary advantage of a NHOM data set is optimized "point verification" (minimum root mean square error) and zero bias for the developmental data as all possible cases are used.

Table 2. Same as Table 1 except for the non-homogeneous (NHOM) developmental data set for CLIPER-GULF.

		MEANS FOR FORECAST PERIOD OF LENGTH						STANDARD DEVIATIONS FOR FORECAST PERIOD OF					
QUANTITY	SYMBOL	12 h	24 h	36 h	48 h	60 h	72 h	12 h	24 h	36 h	48 h	60 h	72 h
Day Number	P1	248.3	248.5	248.6	248.7	248.9	249.1	43.4	43.8	44.2	44.8	45.5	46.4
Initial Latitude	P2	21.5	21.3	21.2	20.9	20.6	20.3	4.7	4.6	4.6	4.5	4.4	4.3
Initial Longitude	P3	89.2	88.7	88.3	87.9	87.5	87.2	5.3	5.1	5.0	4.9	4.9	4.9
Current Meridional Speed	P4	4.0	4.2	4.3	4.4	4.5	4.6	4.1	4.0	3.9	3.8	3.6	3.5
Current Zonal Speed	P5	-4.6	-4.4	-4.2	-3.9	-3.7	-3.5	5.1	5.0	5.0	4.9	4.7	4.6
12 h Past Meridional Speed	P6	3.8	3.9	4.0	4.1	4.2	4.2	3.8	3.7	3.6	3.6	3.5	3.4
12 h Past Zonal Speed	P7	-5.2	-5.0	-4.8	-4.6	-4.4	-4.2	4.9	4.9	4.9	4.8	4.7	4.6
Maximum Wind	P36	57.7	58.7	59.0	58.8	58.2	57.3	24.1	24.4	24.6	24.5	24.2	23.7
12 h Meridional Displacement	DY12	48.6	51.5	53.9	55.1	56.1	56.7	52.7	50.0	48.2	46.4	44.2	42.5
24 h Meridional Displacement	DY24	-----	105.3	110.7	113.9	116.0	117.3	-----	102.0	97.0	92.4	87.3	83.1
36 h Meridional Displacement	DY36	-----	-----	169.7	175.5	179.3	181.3	-----	-----	148.0	139.0	130.2	122.9
48 h Meridional Displacement	DY48	-----	-----	-----	239.2	245.1	248.2	-----	-----	-----	188.8	173.3	162.4
60 h Meridional Displacement	DY60	-----	-----	-----	-----	313.6	318.0	-----	-----	-----	-----	219.2	202.8
72 h Meridional Displacement	DY72	-----	-----	-----	-----	-----	391.0	-----	-----	-----	-----	-----	247.0
12 h Zonal Displacement	DX12	-50.5	-47.9	-45.1	-42.1	-39.4	-36.4	63.5	62.4	61.6	60.1	57.9	55.9
24 h Zonal Displacement	DX24	-----	-85.6	-79.8	-73.8	-68.1	-62.1	-----	128.2	125.7	122.3	117.5	113.1
36 h Zonal Displacement	DX36	-----	-----	-103.5	-94.6	-86.0	-76.5	-----	-----	195.8	188.9	180.6	173.4
48 h Zonal Displacement	DX48	-----	-----	-----	-104.4	-92.6	-80.0	-----	-----	-----	262.4	249.2	238.7
60 h Zonal Displacement	DX60	-----	-----	-----	-----	-88.0	-71.9	-----	-----	-----	-----	324.3	308.9
72 h Zonal Displacement	DX72	-----	-----	-----	-----	-----	-53.5	-----	-----	-----	-----	-----	386.5
Number of Cases	N	3246	2940	2638	2337	2048	1797						

Difficulty arises, however, when a NHOM set is used in a basin such as the Gulf of Mexico where many dissipations occur and the statistical attributes of the sample vary with changing forecast time. As the forecast period lengthens, the bias resulting from dissipations becomes more pronounced and, at 72 h, the NHOM and HOM sets are identical. The result is an acceleration in the forecast tracks in the direction of the mean track favored by the dissipation-induced bias, which, in the Gulf of Mexico, is a northward-moving track. In extreme cases, the forecast track may actually double back on itself. Figure 3 shows two forecasts for Hurricane Anita of 1977, using HOM and NHOM-based equations. Although the NHOM track actually verifies better, the spurious "kink" in the track would likely result in the track being disregarded by the operational forecaster. The necessity of providing the forecaster with a "believable" track is discussed by Neumann (1972) and Neumann and Mandal (1978) in connection with retention of insignificant predictors. It is felt that the same reasoning also applies here.

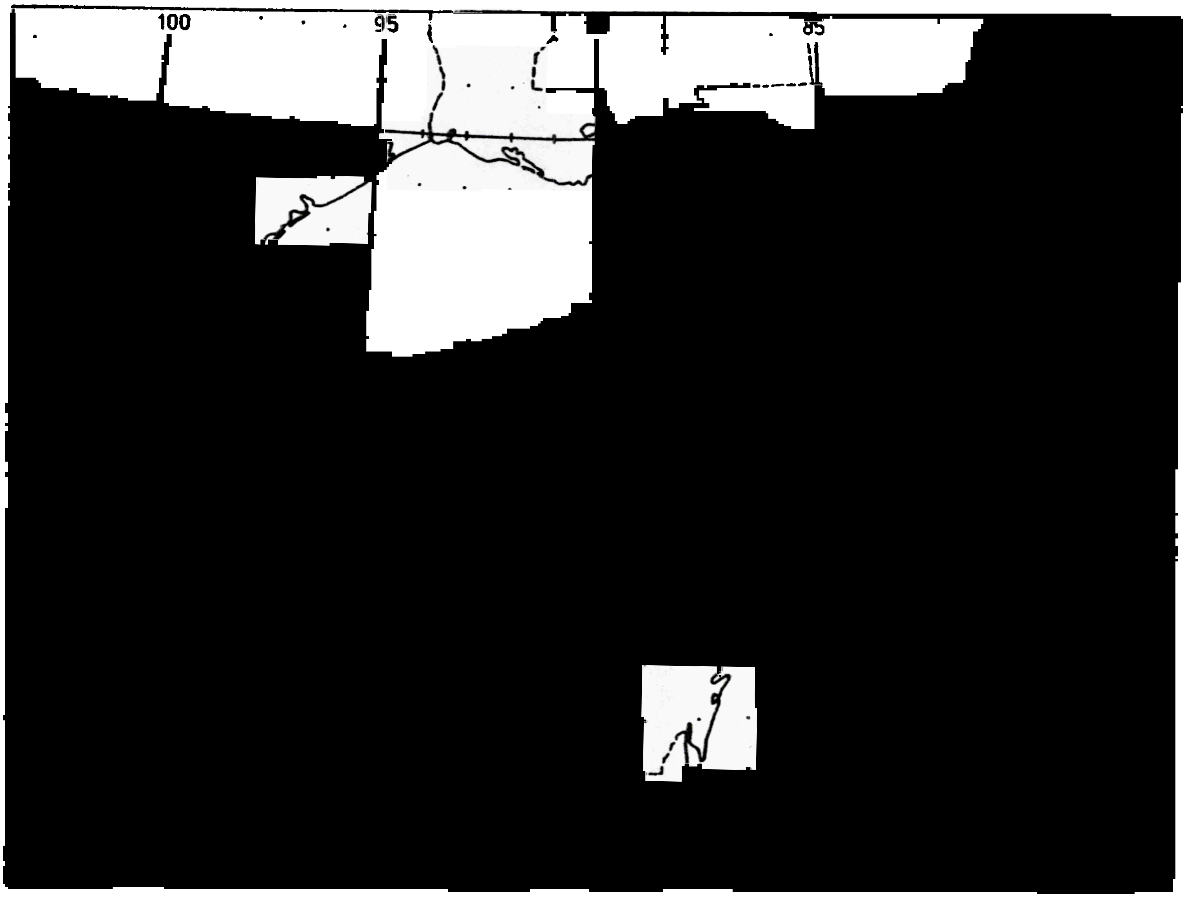

Figure 3. CLIPER-GULF forecasts for Hurricane Anita of 1977 using equations based on HOM (triangles) and NHOM (squares) developmental data sets. The circles are best-track positions at 12 h intervals.

C Extrapolated Non-Homogeneous Data Set

The extrapolated non-homogeneous (ENH) data set represents an effort to retain the optimized verification properties of the NHOM data, particularly at short range, while at the same time reducing the dissipation-induced bias and providing a realistic forecast track. For the first 36 h, this set consists of the NHOM data. Beyond 36 h, the observed displacements are used if available. If not, the remaining displacements at 48, 60 and 72 h are computed by linear extrapolation of the cyclone motion during the 12 h preceding the final position available. An example of this linear track extrapolation is shown in Figure 4, and the statistical properties of the ENH data set are presented in Table 3.

The justification for the use of these linearly extrapolated tracks is based on two main premises. First, tropical cyclone best tracks are sometimes terminated due to lack of either data or operational need even though an identifiable circulation exists. Such situations arise over mainland China (Jarrell and Wagoner 1973) and along the Mexican Gulf coast, although

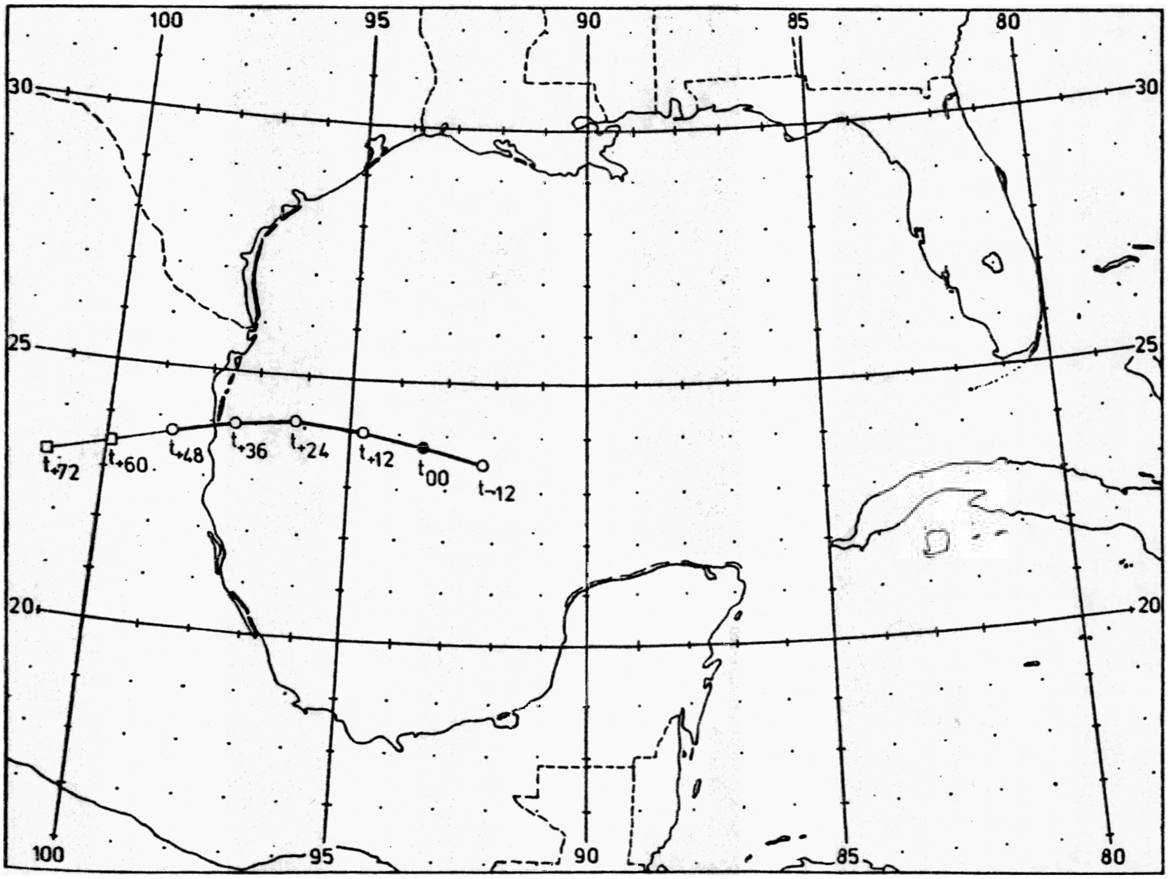

Figure 4. Example of linear track extrapolation procedure used in preparing ENH data set. The circles are available best-track positions and the squares are extrapolated positions computed using the observed displacement from 36 to 48 h.

not nearly as often in the latter area in recent years. One possible, but very time-consuming, solution is a review of the records in an attempt to extend the best tracks for some of the cases. Another justification for track extrapolation arises because statistical models are inherently unable to predict dissipation. A discrete region with a high incidence of dissipations is statistically interpreted as an area into which tropical cyclones seldom move. What is needed for forecasting cyclone motion is an estimate of the steering influences carrying the cyclone into such an area--the question of whether or not the cyclone survived the journey is irrelevant as far as motion prediction is concerned. Track extrapolation is an effort to represent the steering influence predominating in an individual case, even though the cyclone itself may have dissipated. Linear extrapolation is adopted as a quick "first guess" and is also justifiable in that the mean motion field for the western Gulf of Mexico is approximately linear.

The advantages of such a data set are optimized point verification at the critical 12, 24 and 36 h forecast times, and a smooth, representative forecast track beyond 36 h. The main disadvantage is that the system will have higher average forecast errors at 48-72 h than HOM or NHOM equations because many of its "better" forecasts (westward into a high-dissipation area) will not be verified.

3. SYSTEM DEVELOPMENT

Using the Atlantic basin tropical cyclone best-track data file (Jarvinen and Caso 1978), seven basic predictors (see Table 4) were read or computed for each tropical cyclone position within the CLIPER-GULF stratification region. In addition to these predictors, which have become almost standard for CLIPER-type models (Neumann and Mandal 1978; Neumann and Randrianarison 1976; and Neumann and Leftwich 1977), wind speed of the cyclone was added as a supplementary predictor. Means and standard deviations of these predictors for the ENH data set are listed in Table 3. In order to partially account for nonlinear effects (Neumann and Mandal 1978), predictors 9

Table 3. Same as Table 1 except for the extrapolated non-homogeneous (ENH) developmental data set for CLIPER-GULF.

		MEANS FOR FORECAST PERIOD OF LENGTH						STANDARD DEVIATION FOR FORECAST PERIOD OF					
QUANTITY	SYMBOL	12 h	24 h	36 h	48 h	60 h	72 h	12 h	24 h	36 h	48 h	60 h	72 h
Day Number	P1	248.3	248.5	248.6	248.6	248.6	248.6	43.4	43.8	44.2	44.2	44.2	44.2
Initial Latitude	P2	21.5	21.3	21.2	21.2	21.2	21.2	4.7	4.6	4.6	4.6	4.6	4.6
Initial Longitude	P3	89.2	88.7	88.3	88.3	88.3	88.3	5.3	5.1	5.0	5.0	5.0	5.0
Current Meridional Speed	P4	4.0	4.2	4.3	4.3	4.3	4.3	4.1	4.0	3.9	3.9	3.9	3.9
Current Zonal Speed	P5	-4.6	-4.4	-4.2	-4.2	-4.2	-4.2	5.1	5.0	5.0	5.0	5.0	5.0
12 h Past Meridional Speed	P6	3.8	3.9	4.0	4.0	4.0	4.0	3.8	3.7	3.6	3.6	3.6	3.6
12 h Past Zonal Speed	P7	-5.2	-5.0	-4.8	-4.8	-4.8	-4.8	4.9	4.9	4.9	4.9	4.9	4.9
Maximum Wind	P36	57.7	58.7	59.0	59.0	59.0	59.0	24.1	24.4	24.6	24.6	24.6	24.6
12 h Meridional Displacement	DY12	48.6	51.5	53.9	53.9	53.9	53.9	52.7	50.0	48.2	48.2	48.2	48.2
24 h Meridional Displacement	DY24	—	105.3	110.7	110.7	110.7	110.7	—	102.0	97.0	97.0	97.0	97.0
36 h Meridional Displacement	DY36	—	—	169.7	169.7	169.7	169.7	—	—	148.0	148.0	148.0	148.0
48 h Meridional Displacement	DY48	—	—	—	230.6	230.6	230.6	—	—	—	201.7	201.7	201.7
60 h Meridional Displacement	DY60	—	—	—	—	293.6	293.6	—	—	—	—	255.5	255.5
72 h Meridional Displacement	DY72	—	—	—	—	—	359.0	—	—	—	—	—	311.2
12 h Zonal Displacement	DX12	-50.5	-47.9	-45.1	-45.1	-45.1	-45.1	63.5	62.4	61.6	61.6	61.6	61.6
24 h Zonal Displacement	DX24	—	-85.6	-79.8	-79.8	-79.8	-79.8	—	128.2	125.7	125.7	125.7	125.7
36 h Zonal Displacement	DX36	—	—	-103.5	-103.5	-103.5	-103.5	—	—	195.8	195.8	195.8	195.8
48 h Zonal Displacement	DX48	—	—	—	-117.5	-117.5	-117.5	—	—	—	273.1	273.1	273.1
60 h Zonal Displacement	DX60	—	—	—	—	-124.9	-124.9	—	—	—	—	354.8	354.8
72 h Zonal Displacement	DX72	—	—	—	—	—	-129.5	—	—	—	—	—	440.3
Number of Cases	N	3246	2940	2638	2638	2638	2638						

through 35 are defined as the products and cross-products of the basic predictors. Predictands are zonal and meridional displacements in nautical miles, either computed from the best-track positions or by linear extrapolation.

Following past experience with such models (Neumann and Randrianarison 1976), it was elected to fit least-squares polynomials to all the predictors, rather than using only selected predictors obtained through a stepwise screening method. The 37 normal equations for the 36 predictor coefficients and the intercept for each forecast equation were solved using the stepwise screening program available at NHC, with the minimum acceptable reduction of variance set at zero. The values of the coefficients for the 12 prediction equations based on the ENH developmental data set are given in the Appendix.

Tables 5 and 6 show the reduction of variance contributed by specific predictors and the total reduction of variance of each regression equation. Only those predictors contributing at least 0.5 percent or more are listed, although all predictors are included in the forecast equations. Most of the variance is, quite reasonably, explained by a term involving initial motion (P4 or P5) although, unlike all other CLIPER-class models inspected, a non-linear term provides the highest reduction of variance at the 48, 60 and 72 h meridional displacements. Also note that the linear term failed to contribute significantly at these times because of a high correlation between P4 and P4xP3.

4. PERFORMANCE CHARACTERISTICS

Preliminary testing of the models based on each of the three data sets was begun by verifying against the NHOM developmental data set. Performance characteristics for the full basin CLIPER (Neumann 1972), HOM CLIPER-GULF, NHOM CLIPER-GULF and ENH CLIPER-GULF are shown in Table 7. The dissipation bias associated with system development also occurs in the verification data and, thus, must be taken into account when evaluating

Table 4. The basic and supplementary predictors for CLIPER-GULF, the symbols representing them in this paper and their units.

PREDICTOR	SYMBOL	UNITS
Day Number (January 1 = 1)	P1	----
Initial Latitude	P2	degrees North
Initial Longitude	P3	degrees West
Current Instantaneous Meridional Speed	P4	knots
Current Instantaneous Zonal Speed	P5	knots
Instantaneous Meridional Speed 12 Hours Ago	P6	knots
Instantaneous Zonal Speed 12 Hours Ago	P7	knots
Maximum Sustained Wind	P36	knots

Table 5. Percent reduction of variance contributed by specific predictors to the CLIPER-GULF meridional displacement equations for the ENH data set. The predictors listed contributed 0.5 percent or more. Totals in parentheses are the percentages of the total variance reduced at each forecast time by the final forecast equations which include all 36 predictors.

PREDICTOR	SYMBOL	12 h	24 h	36 h	48 h	60 h	72 h
V	P4	89.6	76.3	63.7			0.5
V_{-12}	P6	1.0	1.1	1.3			
VxD	P4xP1				0.5	0.6	
VxX	P4xP3				53.9	47.6	44.1
UxY	P5xP2				1.6	1.9	2.3
UxX	P5xP3		0.7	1.2			
UxV	P5xP4		0.8		0.6		0.5
V_{-12}xX	P6xP3				1.2	0.5	
V_{-12}xU	P6xP5					1.0	
V_{-12}xV_{-12}	P6xP6					1.0	0.9
U_{-12}xU_{-12}	P7xP7				0.5	0.5	
COLUMN TOTALS		90.6	78.9	66.2	58.3	53.1	48.3
TOTAL FOR ALL PREDICTORS		(91.3)	(79.5)	(68.9)	(60.3)	(54.7)	(51.7)

Table 6. Same as Table 5 except for zonal displacement prediction for CLIPER-GULF.

PREDICTOR	SYMBOL	12 h	24 h	36 h	48 h	60 h	72 h
D	P1			1.4	1.8	2.5	1.7
U	P5	91.9	81.4	70.2	60.4	53.1	48.5
U_{-12}	P7	1.0					
DxD	P1xP1				0.5		0.8
DxY	P1xP2				0.6	0.7	
YxY	P2xP2			1.2			1.7
VxY	P4xP2				4.3	5.3	6.1
VxX	P4xP3				0.5		
VxV	P4xP4			0.5			
UxV	P5xP4		0.8				
U_{-12}xD	P7xP1			0.5			
U_{-12}xY	P7xP2				1.5	1.4	1.4
U_{-12}xV	P7xP4		1.6	3.0		0.5	0.8
W	P36				0.5	0.7	
COLUMN TOTALS		92.9	83.8	76.8	70.1	64.2	61.4
TOTAL FOR ALL PREDICTORS		(93.6)	(86.2)	(79.0)	(72.1)	(66.9)	(63.4)

results. As discussed earlier, NHOM CLIPER-GULF has the best verification (minimum average forecast error), with HOM, ENH and CLIPER having progressively greater average errors. ENH and NHOM are, of course, identical at 12, 24 and 36 h. NHOM also possesses the lowest standard deviation of forecast error. Biases are somewhat differently distributed than was expected, with CLIPER actually showing a southward bias at 60 and 72 h. NHOM shows the expected near-zero biases, as the verification sample is identical to the NHOM developmental data. The southwest bias of ENH forecasts results from the dissipation of some of the westward-moving tropical cyclones in the verification sample.

The four equation sets were also verified against a 10-storm, randomly selected, independent data set with results shown in Table 8. Mean forecast errors are higher than for the developmental data beyond 24 h, but the four models can still be ranked in the same order (NHOM, HOM, ENH and CLIPER) on the basis of mean forecast error. The full basin CLIPER here reveals a pronounced bias to the northeast, and all but ENH have a bias to the north. As observed in developmental data testing, ENH again shows a bias to the west at long forecast periods.

Because of the reliance of these models on persistence for most of their variance reduction, use of operational data rather than best-track or post-analysis data inevitably degrades system performance. Operational input for CLIPER has been archived since the beginning of the 1972 season, and was used to verify the four equation sets. The forecast errors are computed

Table 7. Comparative performance of full basin CLIPER and HOM, NHOM and ENH CLIPER-GULF on dependent data. All distances are given in nmi, with north and east considered positive.

TIME	CASES	MEAN ERROR				STANDARD DEVIATION				NORTHWARD BIAS				EASTWARD BIAS			
		Full	HOM	NHOM	ENH	Full	HOM	NHOM	ENH	Full	HOM	NHOM	ENH	Full	HOM	NHOM	ENH
12	3246	18	18	17	17	15	15	15	15	1	0	0	0	1	3	0	0
24	2940	60	56	53	53	43	42	41	41	4	2	0	0	5	10	0	0
36	2638	114	103	99	99	77	75	73	73	4	3	1	1	6	14	-1	-1
48	2337	174	154	151	151	112	106	104	106	3	3	1	-2	3	15	0	-7
60	2048	238	204	203	208	146	135	134	140	1	2	2	-4	-7	10	0	-21
72	1797	301	253	253	264	178	163	163	175	-12	1	1	-6	-23	1	1	-43

Table 8. Same as Table 7 except for a 10-storm independent data sample.

TIME	CASES	MEAN ERROR				STANDARD DEVIATION				NORTHWARD BIAS				EASTWARD BIAS			
		Full	HOM	NHOM	ENH	Full	HOM	NHOM	ENH	Full	HOM	NHOM	ENH	Full	HOM	NHOM	ENH
12	130	19	19	18	18	14	15	15	15	4	3	0	0	2	3	-2	-2
24	116	63	58	56	56	42	41	46	46	18	17	7	7	8	9	-8	-8
36	103	132	118	117	117	90	80	91	91	38	34	21	21	14	11	-16	-16
48	88	200	180	178	180	128	116	123	131	62	52	36	29	37	20	-7	-24
60	75	278	250	247	263	174	157	163	180	76	55	46	23	54	18	1	-49
72	64	354	315	315	349	209	192	192	234	79	40	40	1	77	14	14	-80

Table 9. Same as Table 7 except for operational data, 1972-1979.

TIME	CASES	MEAN ERROR				STANDARD DEVIATION				NORTHWARD BIAS				EASTWARD BIAS			
		Full	BOM	NBOM	ENH	Full	BOM	NBOM	ENH	Full	BOM	NBOM	ENH	Full	BOM	NBOM	ENH
12	175	48	46	47	47	30	29	30	30	-1	-2	-3	-3	-2	-2	-6	-6
24	163	101	96	99	99	60	59	61	61	1	-2	-7	-7	2	0	-13	-13
36	144	156	147	153	153	90	89	93	93	8	2	-7	-7	5	-2	-25	-25
48	126	226	211	215	222	124	123	126	130	20	11	4	-5	14	-4	-29	-41
72	96	370	331	331	365	188	205	205	228	66	43	43	12	28	-21	-21	-103

by preparing forecasts from the operational data, and then vectorially removing the initial positioning error. The result is a forecast displacement error rather than a forecast position error. Forecast displacement error is the standard measure of the accuracy of a tropical cyclone motion forecast used at NHC (Neumann and Pelissier 1980). These displacement errors are listed in Table 9.

As these comparative tests showed no serious reduction of accuracy by the track extrapolation technique, even at long range, and showed a reduction of the northward bias by the ENH equations, they were adopted as the forecast equations for the operational CLIPER-GULF. The average errors of the ENH equations on developmental data and two sets of operational data are depicted graphically in Figure 5. The second operational data curve, that for

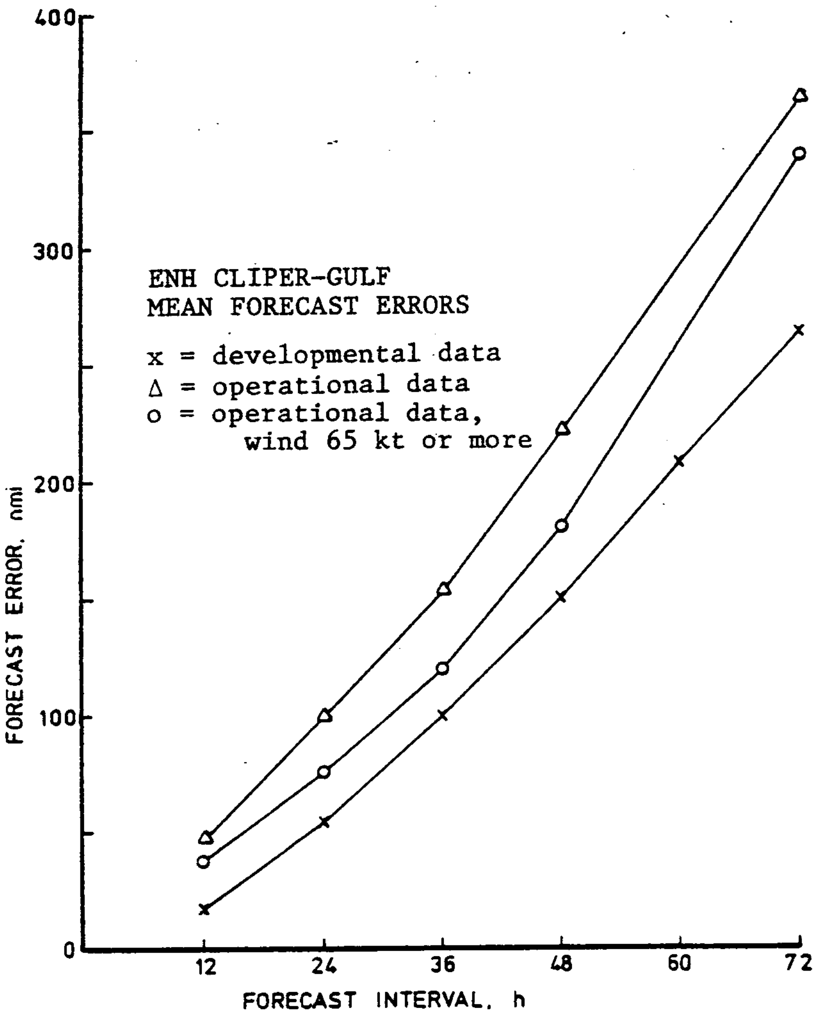

Figure 5. Mean forecast errors for the operational CLIPER-GULF based on the ENH data set.

tropical cyclones of hurricane strength (winds greater than 64 kt), illustrates the improvement of accuracy associated with the better position and motion estimates available for these more organized tropical cyclones. A comparison of the biases of CLIPER and CLIPER-GULF on operational data is shown in Figure 6. The westward bias of CLIPER-GULF is due, in part, to the fact that forecasts of westward-moving cyclones, on which CLIPER-GULF is designed to perform well, are often not verified because of cyclone dissipations.

5. OPERATIONAL CONFIGURATION

ENH CLIPER-GULF has been incorporated into the NHC operational statistical guidance package as a subroutine accessed by the CLIPER model. CLIPER forecasts which serve as input to other models and are given directly to the forecaster now consist of a weighted average of CLIPER and CLIPER-GULF. The weighting function is described in Figure 7. CLIPER-GULF will be activated whenever a cyclone is positioned to the west of the 0.00 line; both individual and composite forecasts will then be included in a supplementary computer message.

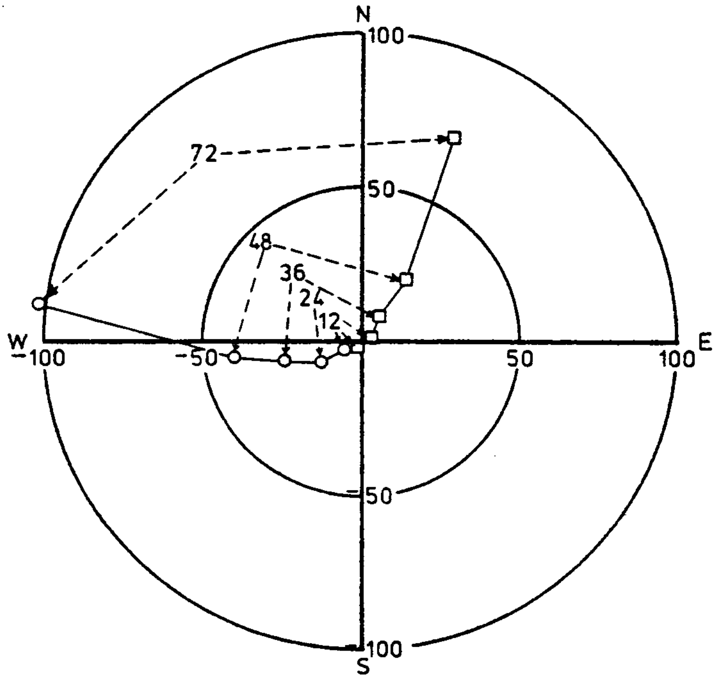

Figure 6. Comparison of forecast biases for the full basin CLIPER (squares) and the operational CLIPER-GULF (circles) for operational data, 1972-1979. The outer circle is 100 nmi.

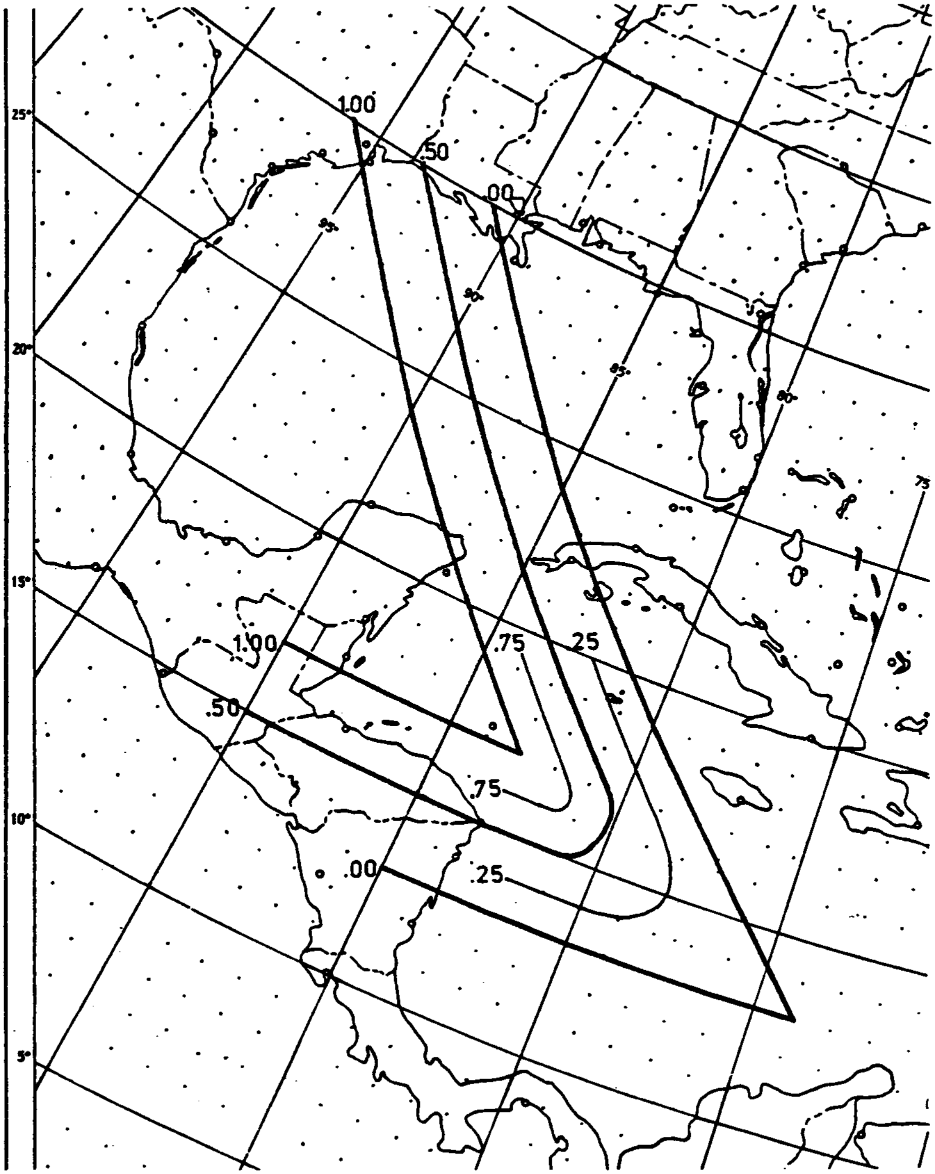

Figure 7. Weighting function for composite CLIPER forecast. The numbered contours give the weight assigned to the CLIPER-GULF system for a tropical cyclone located at that point.

Figures 8-11 illustrate some of the characteristics of the CLIPER-GULF system. Figure 8 depicts the forecast tracks resulting as day number is allowed to vary and other predictors are held constant. The maximum westward motion is to be expected in July and August, and the track shifts eastward in late season, reflecting the increased dominance of the mid-latitude westerlies at lower latitudes. Figure 9 shows the effect of an increase in wind from 45 to 120 kt--the stronger cyclone is forecast to move slightly faster. Also shown is a forecast for a stationary cyclone with 65 kt

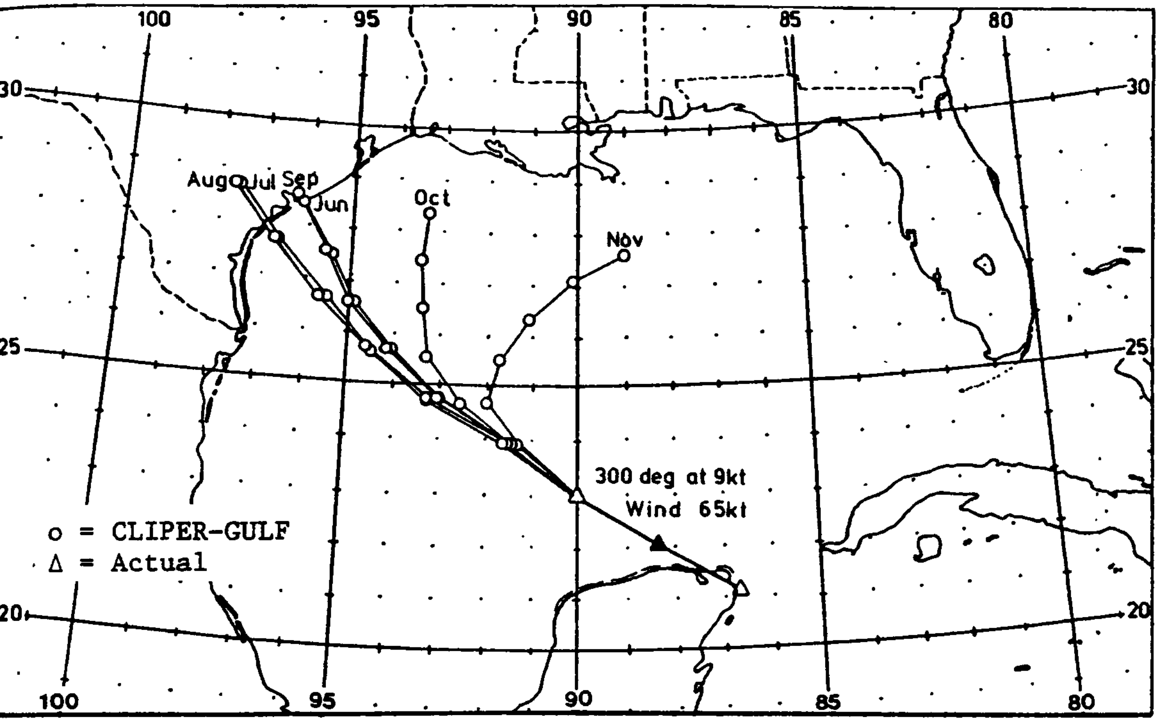

Figure 8. Effect of variation of date on CLIPER-GULF forecast tracks. Tracks were run for the 15th day of the indicated month.

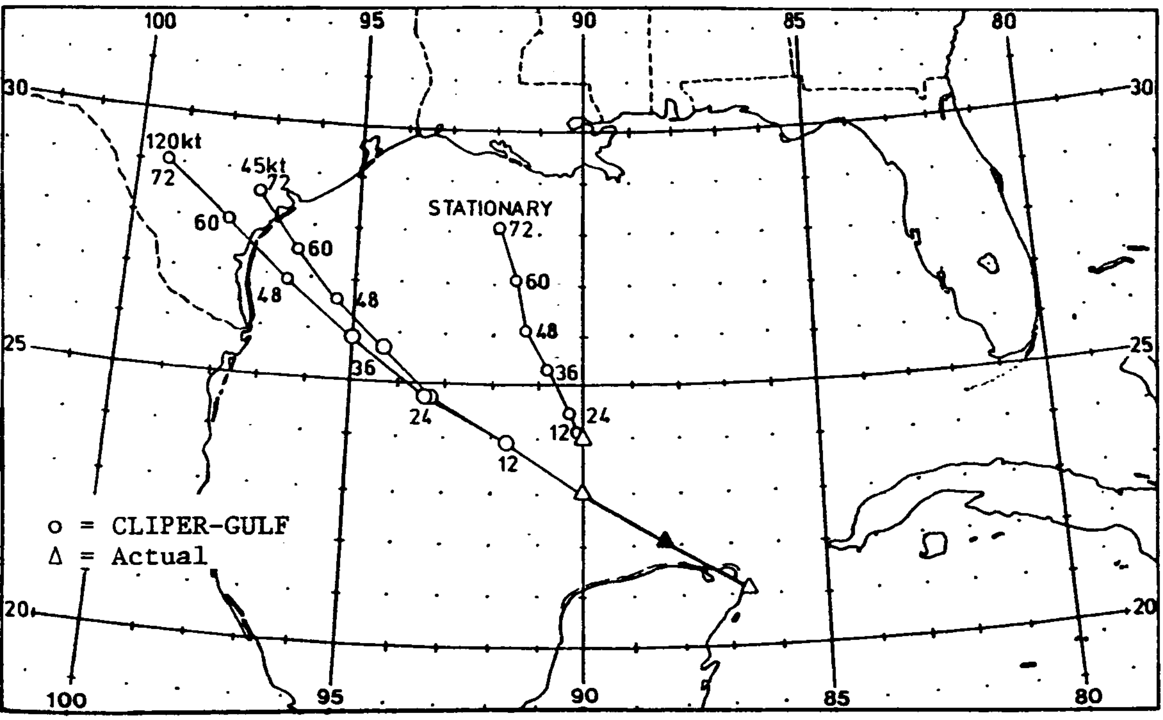

Figure 9. Effect of a variation in wind speed on CLIPER-GULF forecast tracks. Forecasts were run for the August cyclone in Figure 8 with winds of 45 and 120 kt. Also shown is the forecast track for a stationary cyclone with 65 kt winds on September 1.

winds on September 1. Figure 10 shows two forecast examples using operational data from the 1975 season. Hurricane Caroline, moving west-northwestward at nearly constant speed, was handled well, while the accelerating motion of Hurricane Eloise resulted in a 72 h forecast error of over 1000 nmi. Systems such as CLIPER-GULF which rely only on persistence and climatology fail in situations of anomalous or rapidly changing synoptic conditions. The reduction of northward bias and the improved performance of CLIPER-GULF versus CLIPER for westward-moving cyclones are shown by the comparison forecasts for Hurricane Anita of 1977 (Figure 11).

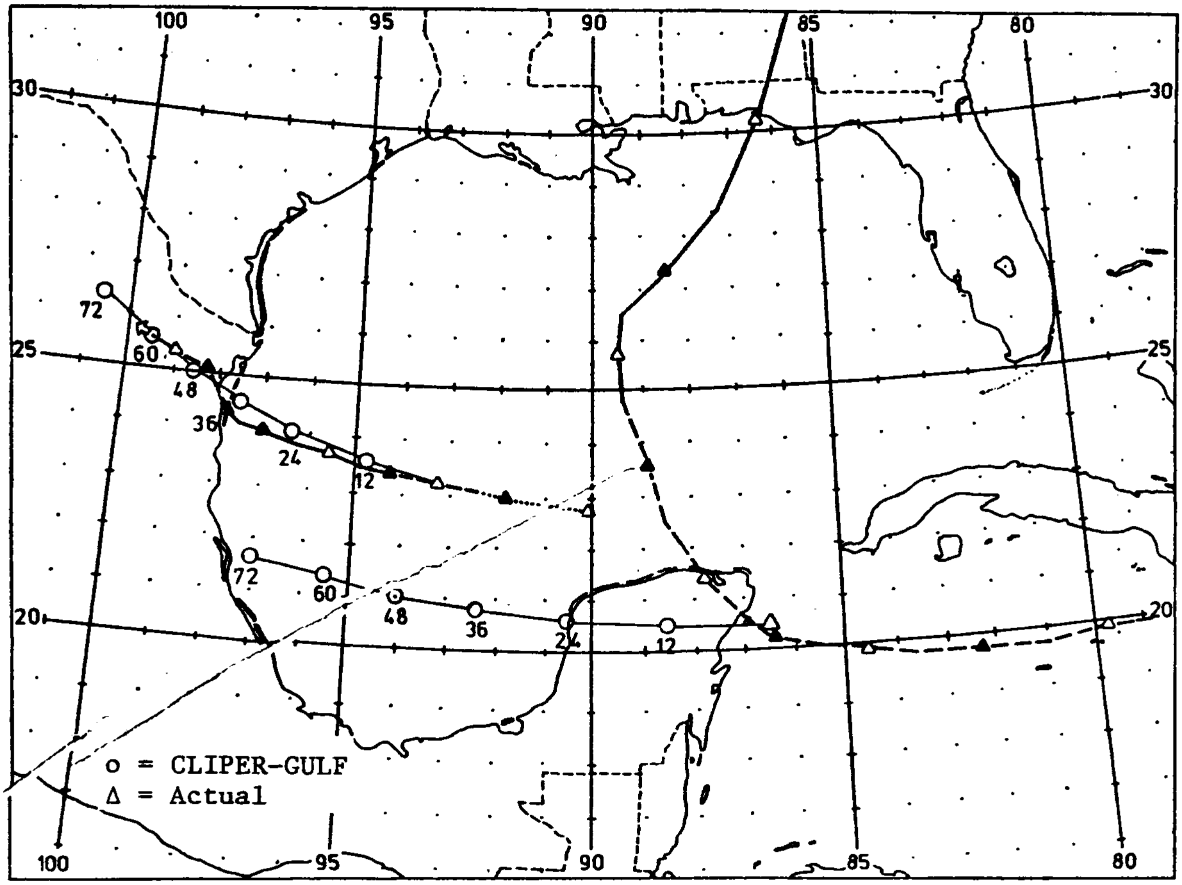

Figure 10. Two forecasts using CLIPER-GULF based on operational data from the 1975 season. Hurricane Caroline (west Gulf) was well forecast, while Hurricane Eloise (central Gulf) was handled poorly.

6. SUMMARY

This paper has described the development of a statistical (climatology and persistence) tropical cyclone motion prediction method for use in the western Gulf of Mexico and northwest Caribbean Sea. The original objective was elimination of the northward bias in the present CLIPER system over the region, but, during the course of this study, the importance of cyclone dissipations within the developmental data became apparent and methodology was developed to "tune" the model to obtain the best performance by using different developmental data sets. The resulting equation set, based on linearly extrapolated non-homogeneous tracks, is the first statistical cyclone motion prediction scheme in which the developmental data were artificially modified in an effort to correct for biases introduced by cyclone dissipation. The CLIPER-GULF system will be operationally tested at NHC and it is hoped that similar approaches will be applied to other basins and additional documentation of and experience with this technique obtained.

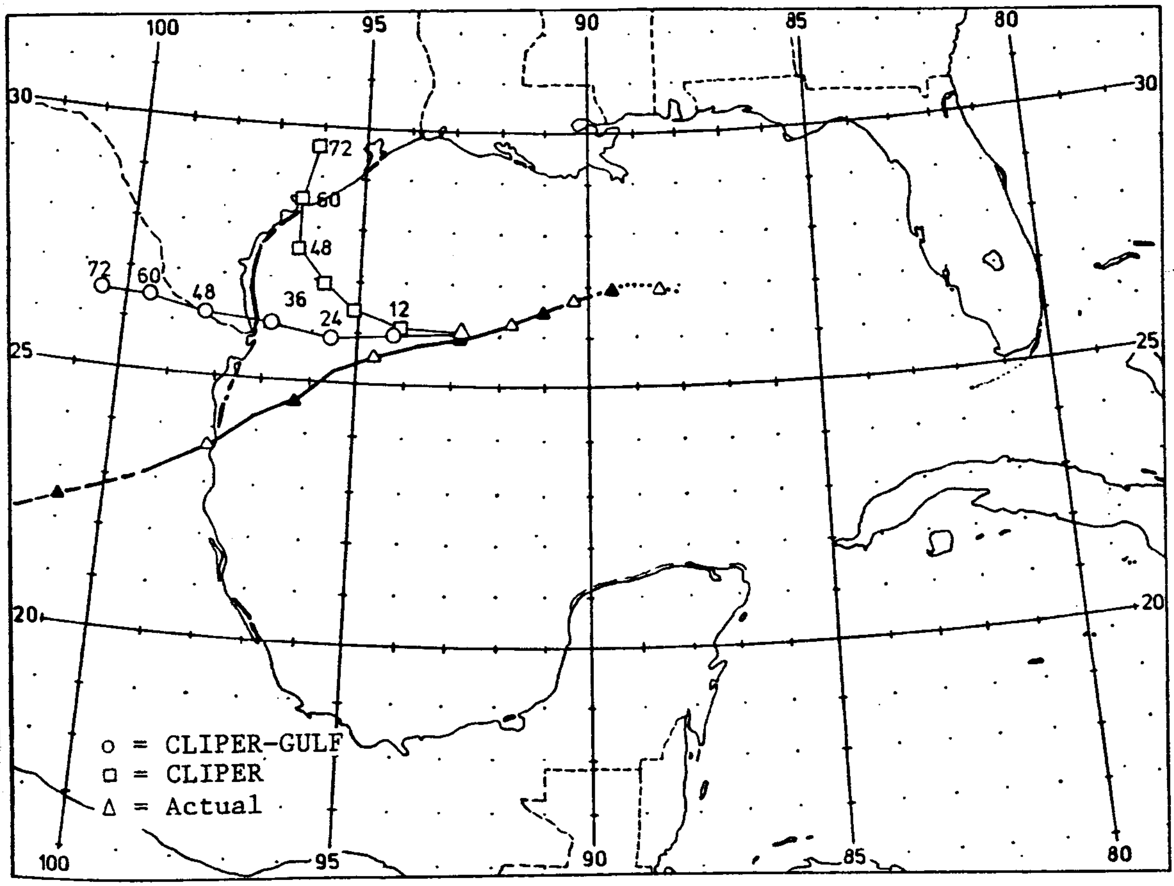

Figure 11. Comparison of full basin CLIPER and operational CLIPER-GULF forecast tracks based on operational data for Hurricane Anita, 1977.

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APPENDIX I. TABLES OF COEFFICIENTS FOR PREDICTION EQUATIONS

The coefficients for the meridional and zonal displacement prediction equations, respectively, are listed on the following two pages. The predictors and their units are specified in Table 4 of the text (p. 9). The predictands are meridional and zonal displacements in nautical miles, with north and east considered positive.

The prediction equations are of the form:

$$D = I + \sum_{i=1}^{36} C_i P_i,$$

where C_i is the coefficient associated with predictor P_i and I is the intercept for a given displacement D.

COEFFICIENTS FOR MERIDIONAL DISPLACEMENTS

PREDICTOR	12 HOUR	24 HOUR	36 HOUR	48 HOUR	60 HOUR	72 HOUR
P1	0.0888784	-0.1899584	-1.2791719	-2.2503653	-2.6821432	-1.4432554
P2	2.0189342	8.6911945	18.5437775	29.2124176	37.0395050	69.0610199
P3	-3.0232592	-7.7038097	-21.4965210	-40.3642426	-60.6247406	-95.5025635
P4	5.0112629	17.8842926	15.7440567	17.0779572	8.3306532	-27.2247925
P5	-0.4663586	1.8958817	13.7586088	17.2671814	21.2920227	29.0697479
P6	-2.2601204	-26.6646576	-56.0136566	-104.0852360	-157.2952420	-193.8726040
P7	1.6083841	0.8565066	-1.0273323	12.0955830	19.9759064	19.9328918
P1xP1	-0.0002354	-0.0005621	-0.0010307	-0.0017919	-0.0033649	-0.0065750
P2xP1	0.0025722	-0.0008909	-0.0173412	-0.0235381	-0.0238942	-0.0171360
P2xP2	0.0380934	0.0850158	-0.0069898	-0.0449264	-0.1273624	-0.0367320
P3xP1	-0.0006782	0.0034124	0.0192933	0.0317965	0.0408996	0.0388394
P3xP2	-0.0451460	-0.1292738	-0.1414892	-0.2155600	-0.2605640	-0.6790639
P3xP3	0.0196852	0.0426631	0.0882439	0.1666921	0.2545010	0.4813834
P4xP1	0.0053249	0.0168735	0.0368659	0.0817288	0.1586019	0.2157335
P4xP2	-0.0941109	-0.1717200	-0.2220821	0.2846074	0.6528067	0.8932160
P4xP3	0.1065220	0.0842524	0.1678605	-0.0195034	-0.1659507	0.0837914
P4xP4	0.0371968	0.0193852	0.1462510	0.2448353	0.3767300	0.4136060
P5xP1	-0.0074174	-0.0207373	-0.0429246	-0.0474278	-0.0510512	-0.0491940
P5xP2	0.0114476	0.1633104	-0.0773177	-0.1532889	-0.2168955	-0.3513719
P5xP3	0.0397118	0.0636077	0.1059194	0.1664857	0.2054711	0.2171922
P5xP4	-0.1690010	-0.5315965	-1.3342285	-1.9062157	-2.1033964	-2.6074772
P5xP5	-0.1136812	-0.4433265	-0.8653569	-1.2207718	-1.6010408	-1.9936008
P6xP1	-0.0028529	-0.0009782	0.0101134	0.0097954	-0.0278351	-0.0604859
P6xP2	0.0703457	0.2091911	0.3178639	-0.1064522	-0.5883789	-1.0243483
P6xP3	-0.0153966	0.1755244	0.4078366	1.0404663	1.8694000	2.4907246
P6xP4	-0.0423261	0.0419906	-0.0984645	-0.2380823	-0.3987695	-0.6472058
P6xP5	0.1190649	0.3086234	0.7358741	0.9551006	1.0662489	1.1425047
P6xP6	0.0001786	-0.0357209	0.0350543	-0.0139472	-0.1142825	-0.0513188
P7xP1	0.0059967	0.0119171	0.0221573	0.0130756	-0.0028696	-0.0240031
P7xP2	-0.0224450	-0.1367056	0.2828421	0.4827187	0.5334598	0.6859001
P7xP3	-0.0375346	-0.0408844	-0.1563257	-0.3369744	-0.3987160	-0.3869234
P7xP4	0.1719109	0.5093530	1.0009460	0.9455972	0.6593722	0.6265983
P7xP5	0.2308200	0.8909345	1.6636229	2.3926725	3.1435699	3.8490620
P7xP6	-0.1857073	-0.5621746	-1.0310659	-0.9962841	-0.9247503	-0.7979159
P7xP7	-0.0995993	-0.3903772	-0.6516668	-0.9012016	-1.2040710	-1.4598370
P36	0.0085389	0.0554313	0.1635486	0.2849380	0.3751197	0.3810998
INTCPT	138.4572750	408.0258790	1203.1201200	2280.3857400	3401.1904300	[illegible]789.4609400

PREDICTOR	12 HOUR	24 HOUR	36 HOUR	48 HOUR	60 HOUR	72 HOUR
P1	-0.6704965	-3.2076530	-6.6781492	-11.2833691	-15.7118349	-20.0923615
P2	1.4162025	18.7032471	45.4614105	67.7041779	97.3614655	140.1359410
P3	-4.6100140	-51.1117706	-144.0815430	-213.4578700	-285.2395020	-364.9216310
P4	1.9871836	5.6067209	-5.8840361	7.2101564	56.3849487	111.3688960
P5	17.5537872	41.0624542	69.7781219	103.3901210	149.2247310	174.4471740
P6	-2.1569490	-5.9989357	-2.2740307	-19.5321045	-68.6964874	-107.3250580
P7	-5.3402338	-10.5029545	-4.6481819	-14.6757727	-40.5299683	-43.3118896
P1xP1	0.0012716	0.0062741	0.0134484	0.0229843	0.0332047	0.0429588
P2xP1	0.0030864	0.0186705	0.0379086	0.0483794	0.0616709	0.0710944
P2xP2	0.0278260	0.1565185	0.3815790	0.4193408	0.4445751	0.5375573
P3xP1	0.0000683	-0.0014309	-0.0039753	-0.0036961	-0.0094752	-0.0133502
P3xP2	-0.0343753	-0.3151049	-0.7343225	-0.9820638	-1.3077641	-1.8051834
P3xP3	0.0304263	0.3294738	0.9044577	1.3240833	1.7742138	2.2847824
P4xP1	0.0099592	0.0497310	0.1020808	0.1520701	0.2035733	0.2595816
P4xP2	0.0788021	0.4094322	1.2687998	2.3483305	3.4630585	4.8826017
P4xP3	-0.0810208	-0.3283910	-0.5415504	-1.0601854	-1.9744339	-3.0362177
P4xP4	0.1417678	0.2947786	0.4282047	0.4061403	0.3229316	0.2986331
P5xP1	0.0012298	0.0020355	0.0083583	0.0143723	0.0249503	0.0258721
P5xP2	-0.0018823	0.0202198	0.2549853	0.9105408	1.5763998	2.1804676
P5xP3	-0.0419311	-0.1759863	-0.4604174	-0.9182075	-1.5356979	-1.8921957
P5xP4	0.0747932	0.1977871	0.0714267	0.0862826	0.1665226	0.2580539
P5xP5	-0.0306750	-0.0611235	-0.0236414	-0.1668057	-0.2893141	-0.5958524
P6xP1	-0.0050167	-0.0238707	-0.0567410	-0.0868560	-0.1269721	-0.1663261
P6xP2	-0.0070392	-0.0192411	-0.3394735	-0.8808472	-1.5389576	-2.3306789
P6xP3	0.0516586	0.1737112	0.3102145	0.7276123	1.5522375	2.2924070
P6xP4	-0.1393882	-0.2251423	-0.4093667	-0.3159147	-0.3514490	-0.7559446
P6xP5	0.0512521	0.3112377	0.5577365	0.5817031	0.5061776	0.7681488
P6xP6	0.0067553	-0.0422888	-0.0197161	-0.0911473	-0.0703315	0.0810918
P7xP1	-0.0037287	-0.0167690	-0.0410260	-0.0663834	-0.1042559	-0.1449324
P7xP2	-0.0017485	0.0152779	0.0190018	-0.4230014	-0.9731485	-1.4833307
P7xP3	0.0441335	0.1156717	0.1124278	0.3969854	0.9226447	1.2019939
P7xP4	-0.2081854	-0.8251600	-1.3487225	-2.0183563	-2.7426901	-3.7551079
P7xP5	0.1950879	0.5527846	0.5703272	0.7029859	0.7652758	1.0364361
P7xP6	0.0235002	0.0455937	-0.0312319	0.2263893	0.5222244	0.7572207
P7xP7	-0.1346830	-0.3788840	-0.3382746	-0.3186548	-0.2770471	-0.3288727
P36	-0.0285769	-0.1737905	-0.4661488	-0.7828428	-1.1405125	-1.4009943
INTCPT	259.4714360	2398.4357900	6604.6718700	9918.9882800	13238.0000000	16794.9414000