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Statistical post-processing of NOGAPS tropical cyclone track forecasts

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THESIS

STATISTICAL POST-PROCESSING OF NOGAPS TROPICAL CYCLONE TRACK FORECASTS

by

Greg A. Ulses

March, 1998

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13. ABSTRACT *(maximum 200 words)*

A statistical post-processing technique is developed and tested to reduce the Navy global model (NOGAPS) track forecast errors for western North Pacific tropical cyclones during 1992-1996. In addition to the basic storm characteristics, the set of 42 predictors includes various track segments in the 00-72 h NOGAPS forecast as well as a 00-36 h backward extrapolation that is compared with the corresponding best-track positions. Although a NOGAPS forecast to at least 36 h is required to calculate the critical backward predictors, a reduced set of forward predictors that did not include the 48- and 72-h NOGAPS positions still produced the same improvement in track forecasts. Separate sets of statistical regressions are developed and tested for three subsets of the synoptic pattern/region combinations defined by Carr and Elsberry. For cyclones in the standard/dominant ridge combination, the improvement relative to NOGAPS is 61% after 12 h, and remains 8% after 72 h. For cyclones in the poleward/poleward-oriented pattern/region, the improvement over NOGAPS is 55% after 12 h, and 6% after 72 h. For a combination of cyclones in all remaining pattern/regions, the improvement relative to NOGAPS is 61% after 12 h, and 10% after 72 h. Comparison of these subsets with a single set of regression equations for all synoptic combinations showed no advantage obtained from using separate equation sets, so the single set is recommended. An independent test with all available 1997 NOGAPS forecasts decreased forecast track error by 50, 22, 12, 9, and 6% at 12, 24, 36, 48, and 72 h.

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STATISTICAL POST-PROCESSING OF NOGAPS TROPICAL CYCLONE TRACK FORECASTS

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Comparison of these subsets with a single set of regression equations for all synoptic combinations showed

no advantage obtained from using separate equation sets, so the single set is recommended. An

independent test with all available 1997 NOGAPS forecasts decreased forecast track error by 50, 22, 12, 9,

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1. BACKGROUND

A. INTRODUCTION

A Systematic and Integrated Approach to Tropical Cyclone (TC) Track Forecasting (hereafter the Systematic Approach) has been developed by Carr and Elsberry (1994; hereafter CE94). The overall objective of the Systematic Approach is to enable forecasters to better improve upon TC track forecasts generated by numerical and objective guidance (CE94). The central thesis of the Systematic Approach is that the forecaster may improve on dynamical and objective track prediction guidance if he/she is equipped with: (*i*) a meteorological data base of dynamically sound conceptual models that classify various TC-environment situations into a reasonably small number of recurring combinations of environment structure and TC structure, and sequences of environment structure change, called transitions; (*ii*) a knowledge base that associates certain types of recurring TC track forecasts with various combinations of TC structure and environment structure; and (*iii*) an implementing methodology or strategy for applying these two knowledge bases by taking account of expected guidance errors. Note that the implementing methodology (*iii*) requires the forecaster to apply adjustments to each dynamical or objective track forecast to account for systematic errors expected in the specific synoptic environment situation.

The Systematic Approach is based on four premises: (i) that TC forecasting is a nonlinear problem in which the track forecast is affected by TC structure (and vice versa) via various modes of interaction between the TC and its environment; (ii) sophisticated dynamical track prediction models that contain an explicit representation of the TC structure are potentially the most accurate source of TC track forecast guidance, since such models explicitly allow for motion-affecting nonlinear interaction between the model representations of the TC and environment; (iii) that present dynamical TC forecast models do not consistently provide track forecasts of acceptable accuracy, because data deficiencies and limitations in model physics and initialization result in imprecise representations of the structure of the environment and

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the TC, and as a result of nonlinear interactions between the TC and its environment; and (iv) that a significant fraction of TC track forecast error generated by sophisticated numerical models or other objective guidance is not random, but rather depends systematically on the particular TC-environment situation (CE94). Premise (iv) will be examined in detail in this thesis.

One characteristic shared by dynamical models has been a systematic error in the forecast track relative to the actual tropical cyclone track (Elsberry and Frill 1980: hereafter EF). The Navy Operational Global Atmospheric Prediction System (NOGAPS) model is the dynamical model that provides primary numerical forecast guidance for Department of Defense activities. The NOGAPS model contains the criteria specified in premise (ii) above; namely, the model contains an explicit representation of the TC structure, and explicitly allows for motion-affecting nonlinear interaction between the model representations of the TC and environment. Thus, the NOGAPS model is the primary track forecast guidance tool used by forecasters at the Joint Typhoon Warning Center (JTWC). In terms of NOGAPS TC track forecasts, the validity of premise (iv) is supported by sets of consistently erroneous track forecasts. Track forecast biases of several techniques relative to mean (actual) S/DR and P/PO TC tracks are shown in Figs. 1a and 1b, respectively. Notice that NOGAPS has a large systematic right-of-track bias for TCs in the S/DR pattern/region (discussion and explanation of pattern/region combinations is presented in Section C). However, the right bias is considerably smaller for the P/PO tracks.

EF discuss a number of possible causes that may account for systematic biases in TC track forecast error, some of which can be applied in some degree to the NOGAPS TC track forecast. First, the NOGAPS model, as in all other operational models, contains an incomplete representation of the physical processes in the tropical cyclone. Most notable is that the central region of intense convection and strong winds is not resolved. Poor resolution of this inner region may cause a systematic phase speed error, as described in Section B. The NOGAPS model utilizes a set of 13 synthetic TC wind vectors to represent the circulation of the TC, with an adjustment so that the sum of the 13 vectors is equal to the recent storm motion (Goerss and Jeffries 1994). The application of these synthetic observations will be examined in

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MODEL BIASES RELATIVE TO MEAN TC TRACK
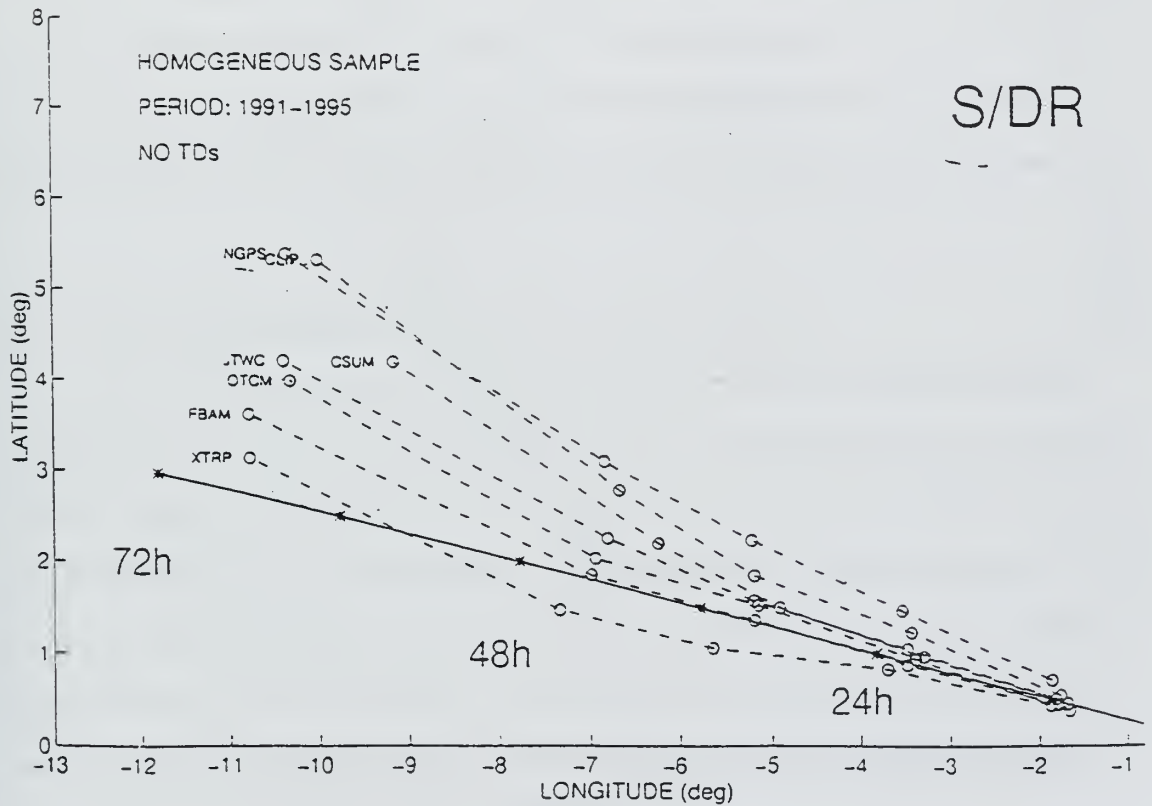
HOMOGENEOUS SAMPLE
PERIOD: 1991-1995
NO TDs

S/DR

Figure 1a. Track forecast biases of several modeling techniques relative to mean (actual) S/DR tracks (provided by L. Carr).
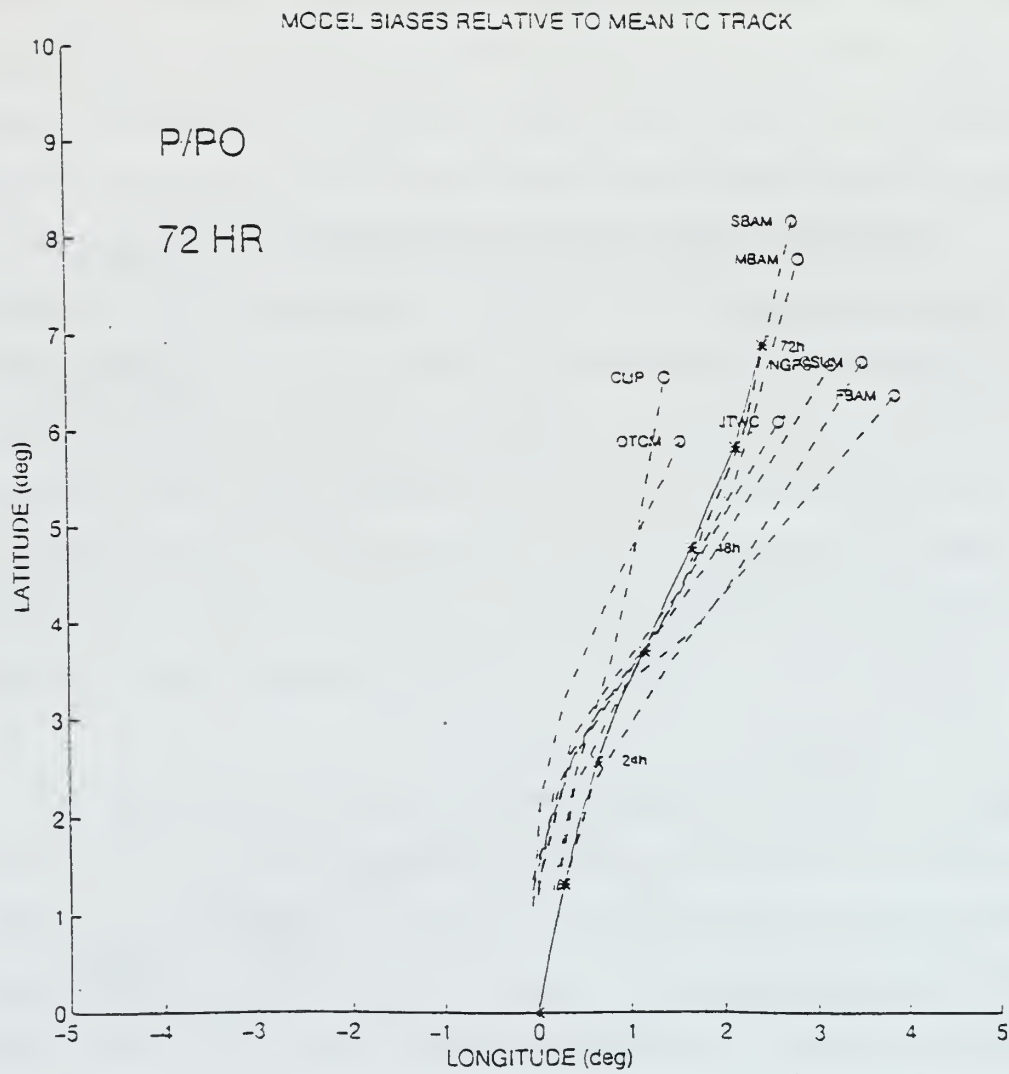
Figure 1b. Track forecast biases of several modeling techniques relative to mean (actual) P/PO tracks (provided by L. Carr).

more detail in the next section. The superposition of this bogus wind field and the pre-existing model vortex from the 6-h NOGAPS forecast may cause unrealistic TC structures and track directions early in the forecast. An overly large initial vortex may also cause systematic, excessive, poleward displacements in the track forecast.

One strategy to overcome and remove systematic track forecast errors is the statistical post-processing of storm tracks. Early efforts to carry out post-processing of dynamical TC track forecasts were conducted by EF. They developed statistical regression techniques for post-processing track forecasts from the Fleet Numerical Meteorology and Oceanography Center (FNMOC) One Way Influence Tropical Cyclone Model (OTCM). In this thesis, many of the EF techniques will be applied to post-process NOGAPS TC track forecasts. Separate sets of statistical adjustments will be derived for some Systematic Approach synoptic patterns/regions. If the addition of the statistical adjustment to the NOGAPS track forecast successfully removes the systematic errors for that pattern/region, the JTWC forecaster will not have to perform step (*iii*) of the Systematic Approach, described at the beginning of this introduction.

B. SYNTHETIC OBSERVATIONS IN THE NOGAPS MODEL

Goerss and Jeffries (1994; hereafter GJ) discuss the use of synthetic TC observations in the NOGAPS model. The purpose of the synthetic observations is to represent the tropical cyclone position, size, and intensity in the global spectral model. The synthetic observations used to depict TC structure are composed of contributions from the large-scale environmental flow and a cyclone-scale vortex. Because of the relatively coarse resolution of the global model, the model depiction of a tropical cyclone vortex is quite different from observed TC structure. Thus, the synthetic observations have been designed to be consistent with how the NOGAPS forecast model depicts tropical cyclones rather than how tropical cyclones actually appear in nature (Goerss *et al.* 1991).

For each storm, soundings are generated at 13 points: one at the position of the storm center; four located 220 km north, south, east, and west of the center; four located at 440 km northeast, southeast, southwest, and northwest of the center; and four located 660 km north, south, east, and west of the center. The vortex component of the synthetic wind observations is derived from a symmetric Rankine profile that fits the maximum wind speed, and the radii of the 30-kt and 50-kt winds reported in the tropical cyclone warning message from JTWC or another forecast center.

The synthetic observations are analogous to rawinsonde soundings and consist of a 1000-mb height, and wind vectors at 1000, 925, 850, 700, 500, and 400 mb. The wind vectors are the sum of the large-scale environmental component and the symmetric vortex component. The warm-core structure of the TC is simulated by decreasing the vortex wind speeds in the vertical by a scaling factor of 1.0 at 1000 mb to 0.65 at 400 mb.

The synthetic TC observations are assimilated into the NOGAPS model by the global multivariate optimum interpolation (MVOI) technique. The MVOI is a statistical analysis that produces fields of geopotential heights and winds on the Gaussian grid of the global spectral forecast model at the 16 standard pressure levels between 1000 and 10 mb. The MVOI is described in more detail by Goerss and Phoebus (1992). The synthetic TC observations are assumed to have the same error properties as radiosondes, which have the highest weightings of any observations in the MVOI. Because these synthetic observations are blended with all other observations and a background field that is a 6-h NOGAPS forecast, the resulting analysis may differ from the synthetic TC observation position and structure.

Following the introduction of the synthetic TC observations in June 1990, notable improvements were achieved in the 48- and 72-h TC track forecasts in the western North Pacific. The impact of the synthetic observations and subsequent improvements in tropical cyclone track forecasts have been noted in several studies. Goerss and Petko (1995) and GJ conducted numerous NOGAPS model runs to compare TC track forecasts both with and without the inclusion of synthetic observations. In all cases, assimilation of

the synthetic observations markedly improved track forecasts. Additional significant improvements were observed after October 1994, when the environment wind structure was required to agree with the recent motion of the TC.

C.   THE SYSTEMATIC APPROACH

As the statistical adjustment to remove systematic NOGAPS track forecast errors is being conducted in the context of the Systematic Approach, a review of the Systematic Approach application is provided for background. In the Systematic Approach, the environment structure (Fig. 2) is defined in terms of synoptic patterns and regions derived from operationally analyzed NOGAPS maps (CE94). Synoptic patterns are classifications of the large-scale environment based on the existence and orientation of various synoptic circulations such as cyclones and anticyclones, or troughs and ridges. Synoptic regions are identified as smaller areas within the synoptic patterns where certain characteristic directions of environmental steering might be expected. Four synoptic patterns and seven synoptic regions (Fig. 2) are defined in the western North Pacific region (CE94). Each synoptic pattern/region combination will be briefly described in this paper. Detailed case studies with analyses, satellite imagery, and tracks are provided by CE94 and Carr *et al.* (1995). A key conclusion from a five-year (Carr *et al.* 1995) and later a seven-year (Carr *et al.* 1998; hereafter CEB98) sample of situations is that characteristic tracks that are distinctly different are associated with each synoptic pattern/region combination.

In the Standard (S) synoptic pattern (Fig. 3), the axis of the subtropical ridge is approximately east-west although it may be slightly tilted longitudinally. This ridge structure may be modulated by a midlatitude trough that introduces a break in the ridge, or the ridge may be relatively thin rather than the broad circulation shown in Fig. 3. Three synoptic regions are defined in the S pattern. The Dominant Ridge (DR) region is poleward of the equatorial trough and equatorward of the subtropical ridge. A separate small synoptic region called the Weakened Ridge (WR) is east of, and relatively close to, the subtropical ridge break in a relatively weak (5-8 kt) southeasterly-to-southerly environmental steering.

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WESTERN NORTH PACIFIC
METEOROLOGICAL KNOWLEDGE BASE

ENVIRONMENT STRUCTURE

P
A
T
T
E
R
N

OPTIONS
Standard (S)   Poleward (P)
Monsoon Gyre (G)   Multiple TC (M)

R
E   OPTIONS
G   Equatorial Westerlies (EW)
I   Dominant Subtropical Ridge (DR)
O   Weakened Subtropical Ridge (WR)
N   Midlatitude Westerlies (MW)
     Poleward-Oriented (PO)
     Multiple TC Poleward Flow (PF)
     Multiple TC Equatorward Flow (EF)

TC STRUCTURE

INTENSITY

OPTIONS
Exposed Low-level (XL)
Tropical Depression (TD)
Tropical Storm (TS)
Typhoon (TY)
Super Typhoon (ST)

SIZE

OPTIONS
Midget (M)   Average (A)
Small (S)   Large (L)

ENVIRONMENT EFFECTS

OPTIONS
Advection by Environment (ADV)
Monsoon Gyre Formation (MGF)
Monsoon Gyre Dissipation (MGD)
Subtropical Ridge Modulation (SRM)

**TC-ENVIRONMENT
TRANSFORMATIONS**

OPTIONS
Beta Effect Propagation (BEP)
Ridge Modification by TC (RMT)
Reverse Trough Formation (RTF)
Monsoon Gyre - TC Interaction (MTI)
Direct TC Interaction (DTI)
Semidirect TC Interaction (STI)
Indirect TC Interaction (ITI)
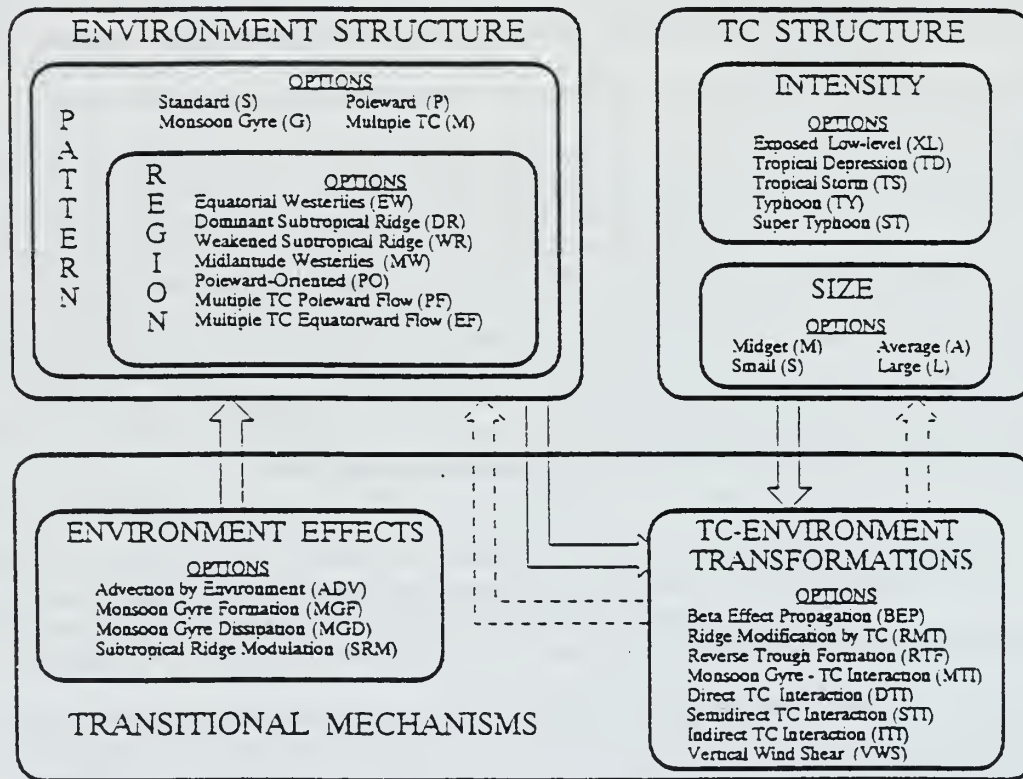Vertical Wind Shear (VWS)

TRANSITIONAL MECHANISMS

Figure 2. Conceptual framework of TC motion effects of environmental structure (upper left), TC structure (upper right), plus TC-environment transformation (lower right), and environmental effects (lower left) as a separate subgroup of transitional mechanisms in the Systematic Approach (From CEB98).

Finally, the Midlatitude Westerlies (MW) synoptic region is poleward of the subtropical ridge axis and east of the ridge break. A TC in the DR region is expected to have a predominantly westward track as shown in sequence 1 in Fig. 3. However, a TC in the WR region may recurve (sequence 2 in Fig. 3) or may have a "failed recurvature" and return to a position equatorward of the ridge axis (sequence 3 of Fig. 3), which is then called a stair-step track. Of the 4017 synoptic environment characterizations in the western North Pacific during 1989-1996, about 60% were in the Standard (S) pattern. A majority (52%) of all assignments was in the Dominant Ridge (DR) synoptic region of the S pattern. The corresponding tracks for the S pattern are given in Fig. 4. Long tracks, generally toward the west to northwest, are associated with the periods when the TCs are in the S/DR combination. Short poleward tracks are associated with the S/WR combination, as TCs move through the subtropical ridge. One possible sequence is for the TC to recurve into the MW region, in which tracks are first northward, and then accelerate northeastward.

In the Poleward (P) synoptic pattern (Fig. 5), the environment structure usually includes a significant subtropical ridge break poleward of the TC, and a prominent, primarily north-south oriented anticyclone to the east that extends equatorward of the TC. Two scenarios during which a P pattern can develop are discussed by CE94. The first occurs when the latitude of the monsoon trough axis increases to the east, which is called a reverse-oriented trough. The second scenario occurs if a single TC is comparatively large relative to adjacent synoptic features. The P pattern can develop after a poleward-oriented anticyclone forms to the east and equatorward of the TC, and CE94 call the associated TC-environment transformation a Ridge Modification by a large TC (RMT). Two synoptic regions are defined in the P pattern. The Poleward-Oriented (PO) region is to the east of the reverse-oriented monsoon trough and extends to a col region near the poleward end of the subtropical ridge. Typical TC motion in the PO region is poleward (Fig. 5). The Midlatitude Westerlies (MW) synoptic region is analogous to the MW region of the S pattern (Fig. 3). The two Dominant Ridge (DR) regions shown in Fig. 5 are considered to be the DR regions of the adjacent S patterns, and are not part of the P pattern.

STANDARD (S) PATTERN
CHARACTERISTIC TRACKS

- - - - - - - - Region boundaries
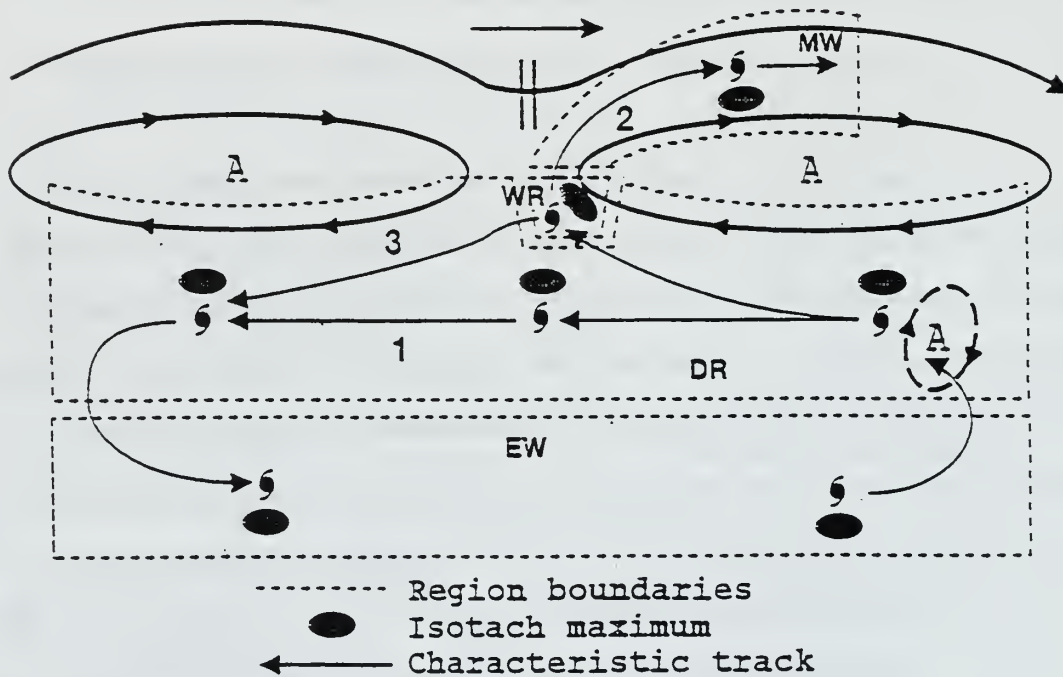⬤ Isotach maximum
◄—— Characteristic track

Figure 3. Schematic of the Standard (S) synoptic pattern conceptual model with the boundaries (dashed) of the associated synoptic region conceptual models added. DR denotes the Dominant Ridge region, WR the Weakened Ridge region, and MW the Midlatitude Westerlies region. Streamlines of an appropriate layer-mean environmental flow with the TC circulation removed are indicated by the thin solid lines with arrows, with A indicating anticyclone. The numbered TC symbols indicate possible sequences of positions (From CEB98).
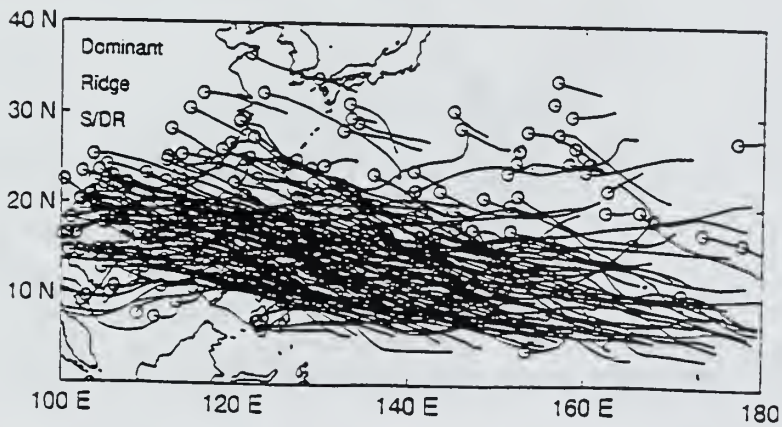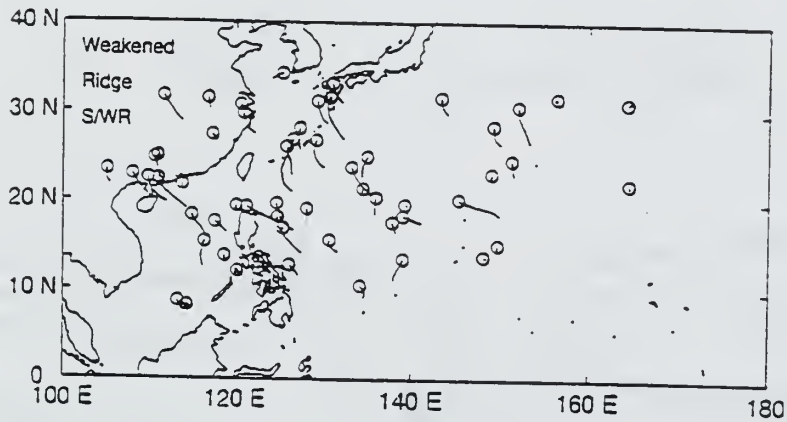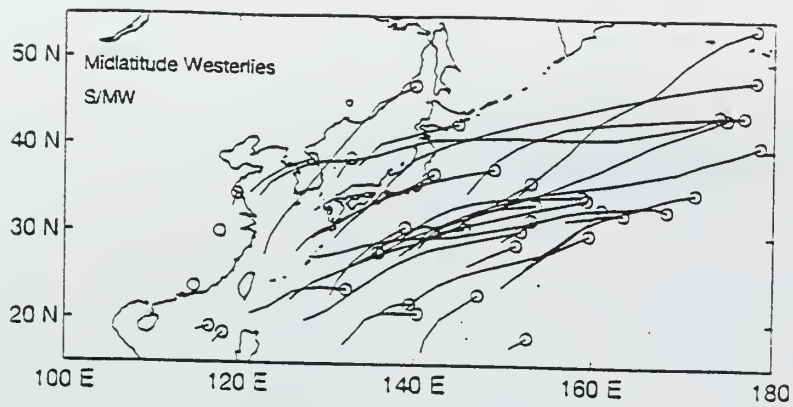
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Figure 4. Storm tracks during 1989-1996 while the storm is in the Standard (S) pattern and the Midlatitude Westerlies, Weakened Ridge, and Dominant Ridge synoptic regions (From CEB98).
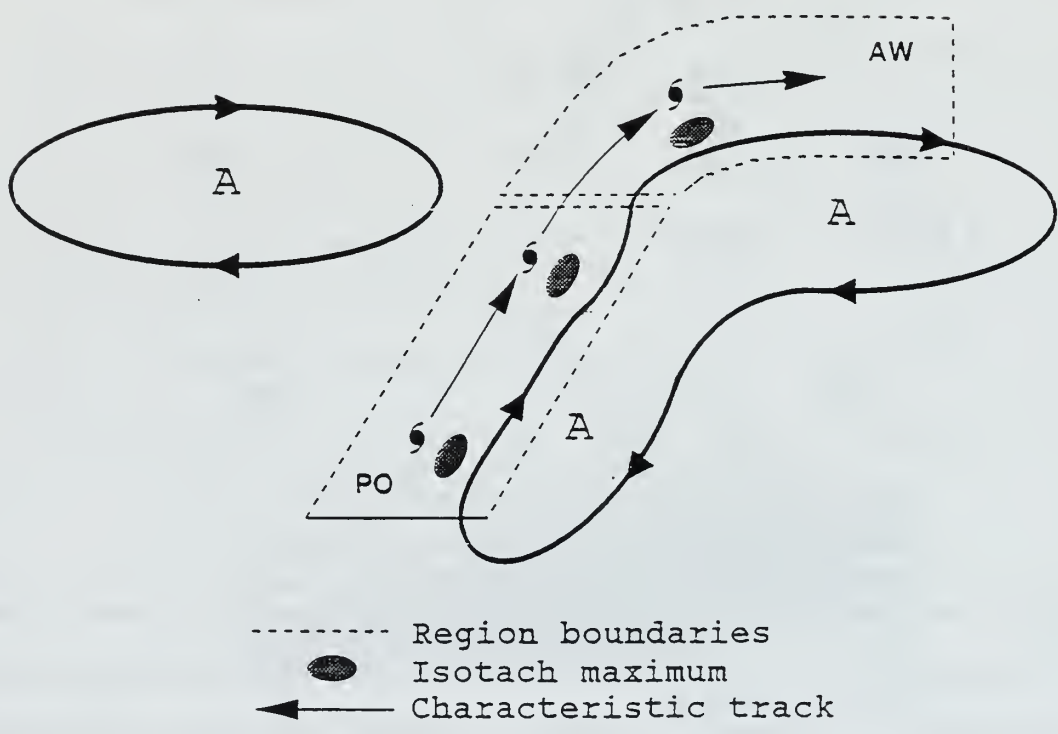
POLEWARD (P) PATTERN
CHARACTERISTIC TRACKS

Figure 5. As in Figure 3, except for the Poleward (P) synoptic pattern and associated synoptic regions, where PO denotes the Poleward-Oriented synoptic region (From CEB98).
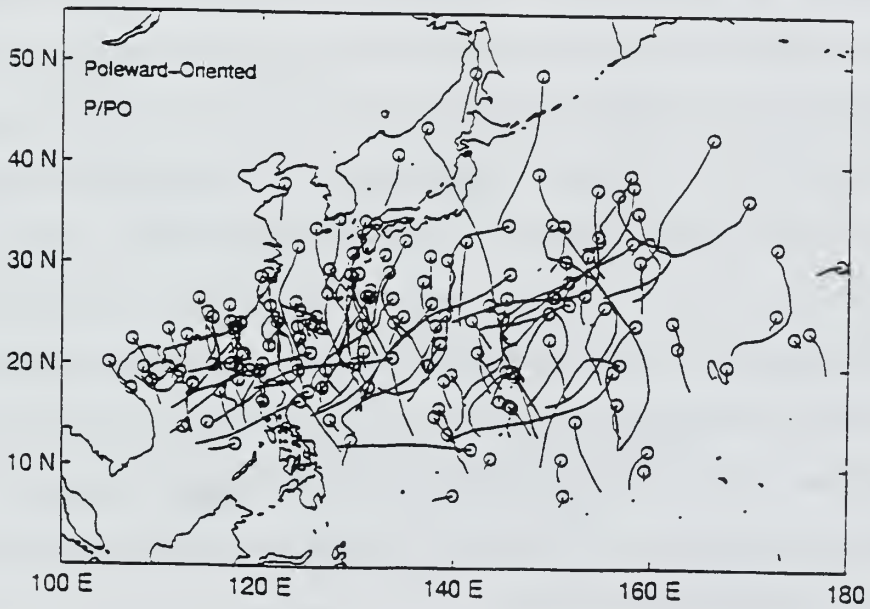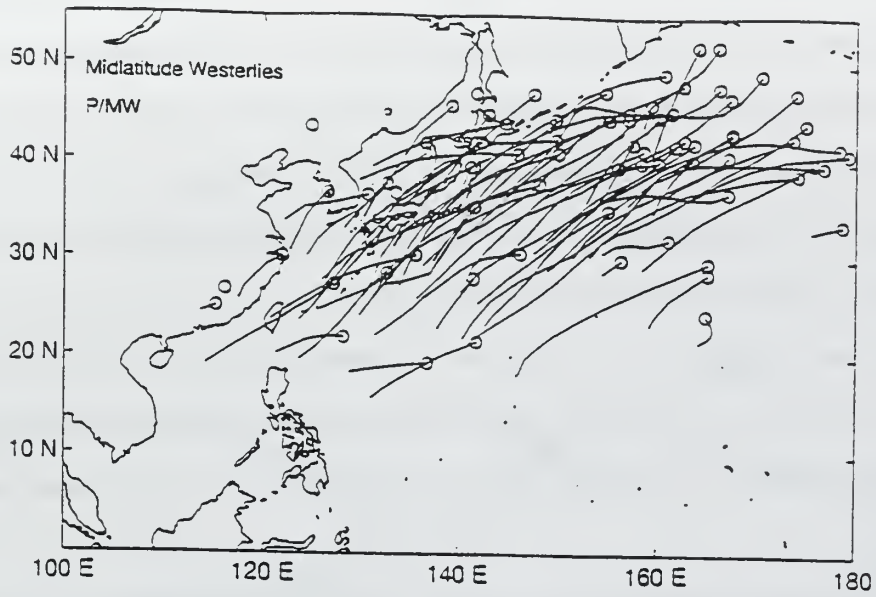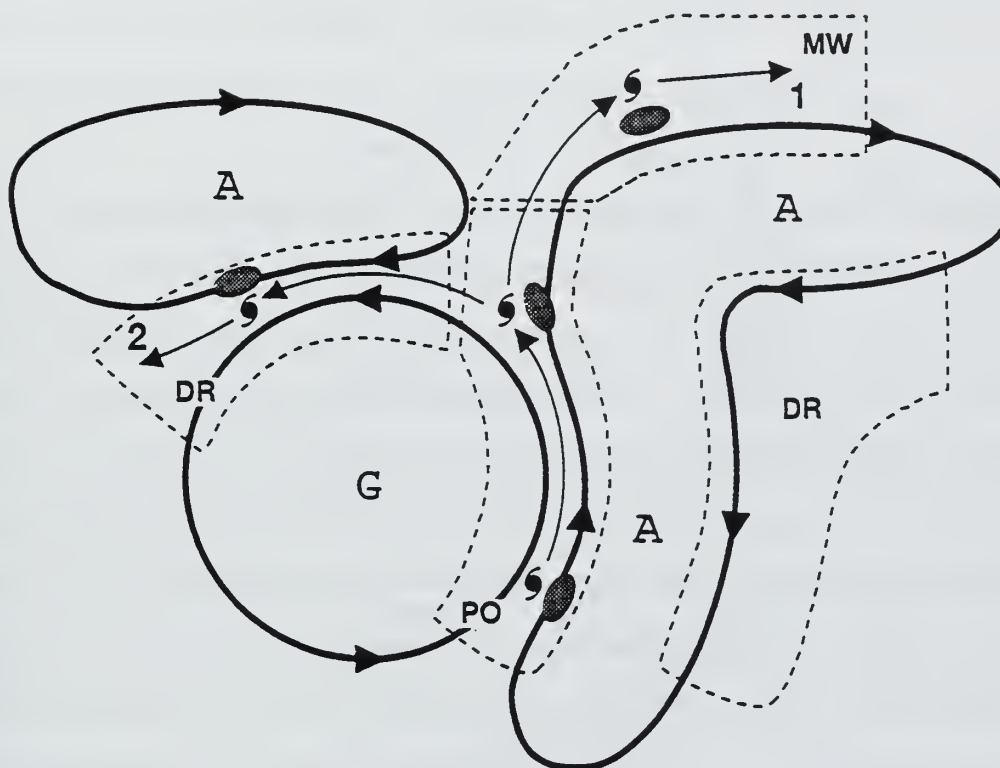
Figure 6. Storm tracks as in Figure 4, except in the Poleward (P) pattern and the Midlatitude Westerlies (MW) and Poleward-Oriented (PO) synoptic regions (From CEB98).

Corresponding tracks from the P pattern are given in Fig. 6. The tracks in the PO region have the expected poleward tracks, but are characterized by large variations in the directions and lengths of tracks, including some sinuous tracks. Notice also that the tracks in the P pattern are different from those in the WR region of the S pattern (Fig. 3). Because the meridional extent of the anticyclone east of the TC in the P/PO combination (Fig. 5) is greater than that of the subtropical anticyclone east of the TC in the S/WR combination (Fig. 3), the storm tracks in the P/MW region tend to be very consistently poleward, although a few more eastward tracks also occur. About 30% of the synoptic environment characterizations are in the P pattern, with 21% in the Poleward-Oriented (PO) region, and the remainder in the Midlatitude Westerlies (MW) region. Notice that about 73% of all cases are in the S/DR and P/PO combinations alone.

The TC environment is classified as a monsoon Gyre (G) pattern when a particular type of large monsoonal circulation is present (Fig. 7). The monsoon gyre is a cyclonic circulation that is significantly larger and usually weaker than the embedded TC. The large monsoon gyre in Fig. 7 will have an extensive anticyclone to the east and southeast, as well as a subtropical anticyclone on the poleward side. The Poleward-Oriented (PO) and Midlatitude Westerlies (MW) synoptic regions in the G pattern are generally the same as in the P pattern (Fig. 5), except the western boundary of the PO region curves around the monsoon gyre. As in the P pattern (Fig. 5), the eastern Dominant Ridge (DR) region is considered to be in the S pattern rather than the G pattern. However, the western DR region in Fig. 7 is included because the east-northeasterly steering in this DR region is influenced by both the gyre circulation and the anticyclone to the north. The TCs will generally have cyclonically curved tracks (sequence 2 in Fig. 7) if the monsoon gyre is quasi-stationary. If the gyre is translating to the west, the TC track will have less cyclonic curvature, and may even be almost westward for a rapidly translating gyre. A bifurcation between TC tracks occurs at the poleward end of the PO region. If the TC is larger than average size, or is on the outer edges of the monsoon gyre circulation, it will tend to transition to the MW region (sequence 1 in Fig. 7). A smaller than average size TC that is closer to the center of the gyre circulation will transition to the DR region (sequence 2 in Fig. 7).

GYRE (G) PATTERN
CHARACTERISTIC   TRACKS

G	Monsoon gyre center
--------	Region boundaries
⬬	Isotach maximum
◄────	Characteristic tracks relative to gyre center

Figure 7. As in Figure 3, except for the monsoon Gyre (G) synoptic pattern and associated synoptic
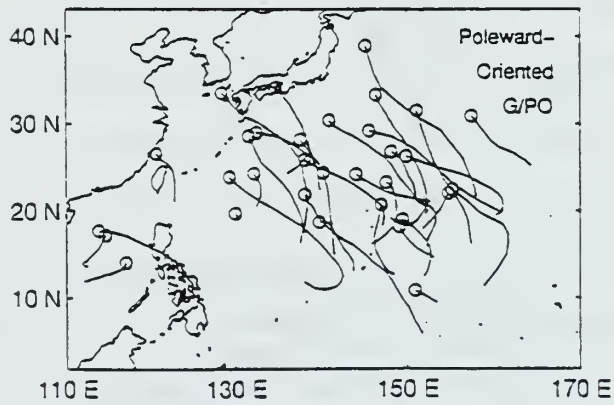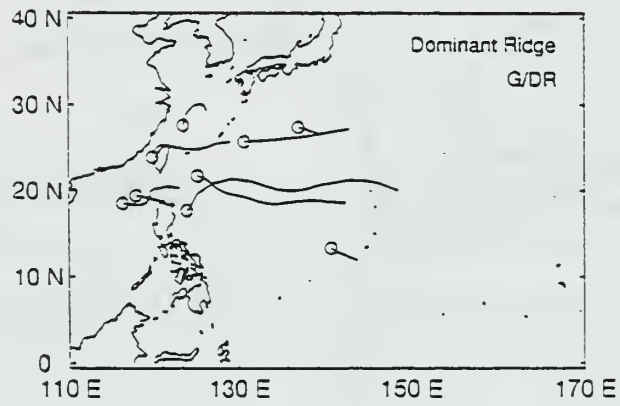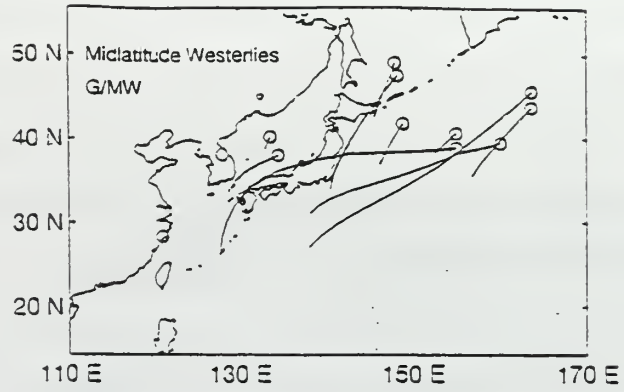
regions (From CEB98).

Figure 8. Storm tracks as in Figure 4, except in the monsoon Gyre (G) synoptic pattern and the Midlatitude Westerlies, Dominant Ridge, and Poleward-Oriented regions (From CEB98).

Corresponding tracks from the G pattern are given in Fig. 8. Notice that most of the analyses are in the PO region of the G pattern, and that tracks are generally cyclonically curved at the beginning. Some of these tracks are quite long, which indicates that the monsoon gyre persisted for some time. Once the TCs arrive at the bifurcation point, they may continue into the DR region or recurve into the MW region. It is clear from the Fig. 8 scenarios that a large difference in tracks occurs depending on how the TC passes through the bifurcation point at the poleward end of the PO region. These bifurcation situations are expected to have lower predictability, and the potential for larger track prediction errors, which will have implications for the statistical adjustment technique developed in this study. Only 7% of the 4017 synoptic environment characterizations studied by CEB98 were in the G synoptic pattern.

The final synoptic pattern/region combinations discussed by CE94 involve the interaction of multiple TCs. In the Multiple (M) synoptic pattern (Fig. 9), the two TCs must be separated by more than 10 degrees latitude and less than about 20 degrees latitude, oriented approximately east-west, and be at a latitude not too far north or south of the subtropical ridge axis. The main feature of the M pattern is that the height gradient between the western TC and the anticyclone to the east establishes a poleward steering flow across the eastern TC (Fig. 9). This is the Poleward Flow (PF) synoptic region, and a TC in this region will move through a recurvature point into the Midlatitude Westerlies (MW) synoptic region without the deceleration noted during other recurvature scenarios. Similarly, the height gradient between the eastern TC and the anticyclone to the west establishes an equatorward steering flow across the western TC. This is the Equatorward Flow (EF) synoptic region, and is shown in Fig. 9. A TC in this region will have a steering flow that opposes the expected poleward and westward beta-effect propagation. These M patterns are not expected to persist very long, as the conditions regarding separation distance and favorable positions relative to adjacent anticyclones do not persist.

Corresponding tracks from the M pattern are shown in Fig. 10. As a rule, tracks in the M pattern are characterized by speeds and directions that differ from more "traditional" tracks. For example, tracks in the M/PF pattern/region are consistent with the expected poleward flow direction between a western TC

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MULTIPLE (M) PATTERN
CHARACTERISTIC TRACKS
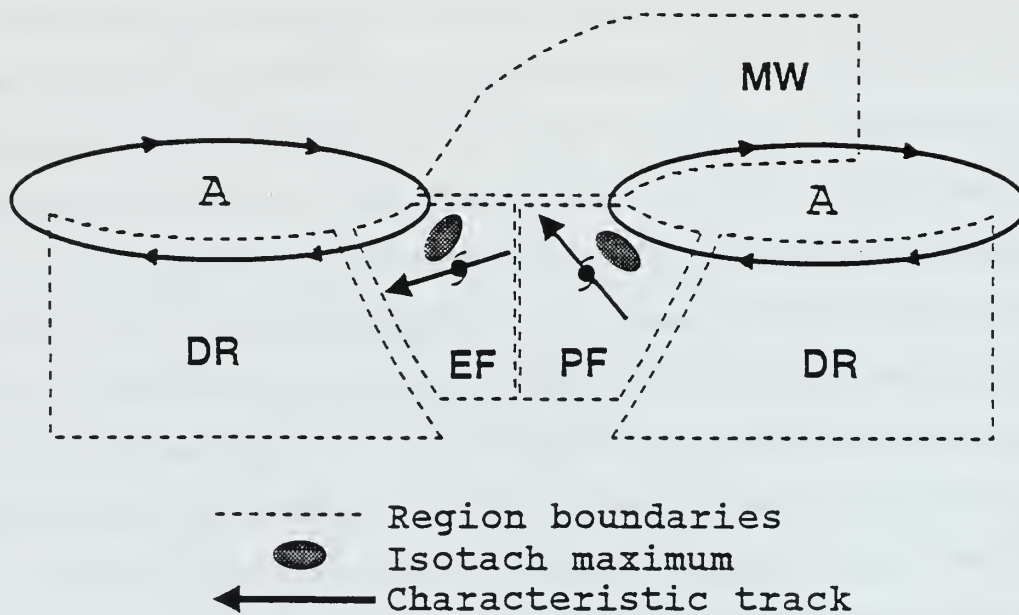
Figure 9. As in Figure 3, except for the Multiple (M) tropical cyclone synoptic pattern and associated synoptic regions, where PF denotes the Poleward Flow region and EF denotes the Equatorward Flow region. The adjoining DR and MW regions (heavy dashed) are not considered to be part of the M pattern (From CEB98).
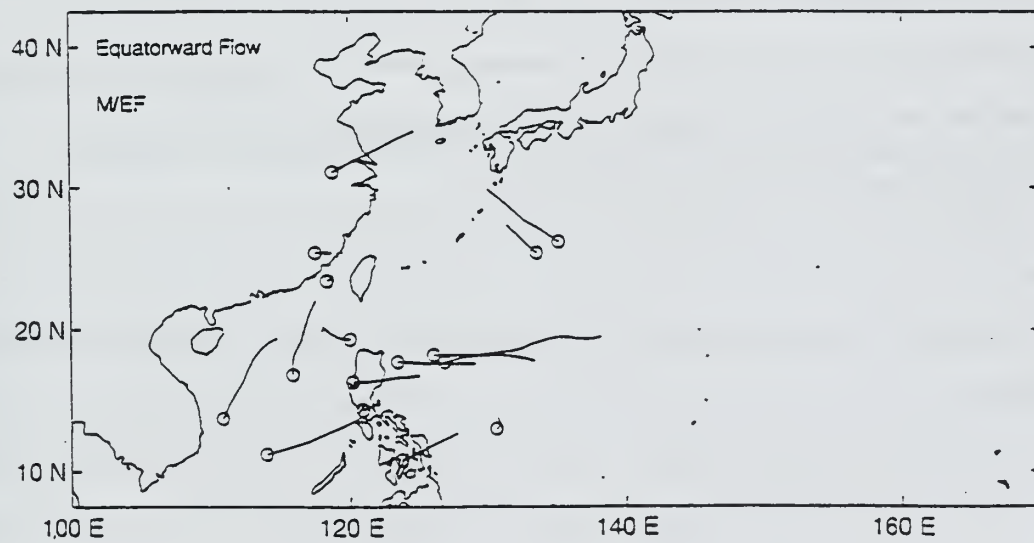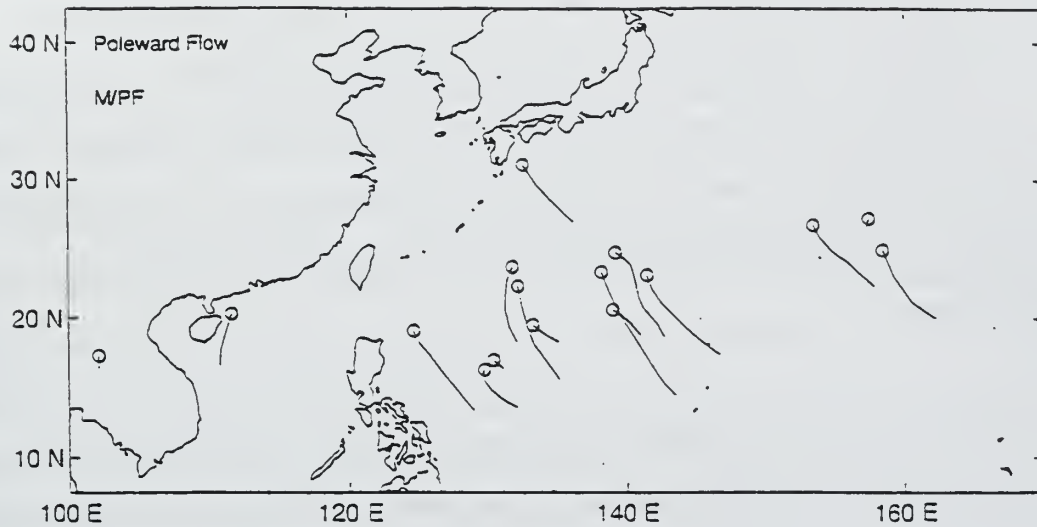
Figure 10. Storm tracks as in Figure 4, except in Multiple (M) synoptic pattern and the Poleward Flow (PF), and Equatorward Flow (EF) regions (From CEB98).

and an anticyclone to the east. However, the translation speeds of these tracks (not indicated in Fig. 10) do not experience the characteristic deceleration, and are typically larger than expected, for a TC approaching the subtropical ridge axis. Tracks in the Equatorward Flow (EF) region are primarily westward and equatorward. In the equatorward (westward) cases, the environmental steering flow dominates (is neutralized by) the beta-effect propagation, which is westward and poleward. As with the Gyre synoptic pattern/region combinations, TC tracks in the M pattern have lower predictability, and the potential for larger track forecast errors. The M pattern cases are relatively rare, and account for only 3% of the cases studied by CEB98. The cases were evenly split between M/PF and M/EF scenarios. Notice that the Gyre and Multiple pattern scenarios account for only 10% of the cases in the data base. The low sample sizes of these two patterns will, along with the more complex nature of the tracks, figure prominently in later sections of this paper.

The basic concepts of the Systematic Approach were introduced to JTWC forecasters early in 1994. Certain portions of the Systematic Approach have been tested by JTWC, and have been employed in a quasi-operational sense since the 1995 typhoon season. The JTWC (1995) has credited the Systematic Approach for their increased track forecast improvement relative to NOGAPS, which is their primary numerical guidance. The Systematic Approach is a forecasting framework that is continuing to evolve via a series of field tests and refinements. As such, the Systematic Approach also serves as a framework to implement ongoing research on TC motion, such as this study.

II.   METHODOLOGY

A.   DEVELOPMENT OF REGRESSION EQUATIONS

1.   Predictands

The regression equations developed for this study are similar to those developed by EF and Peak and Elsberry (1982). Consider the NOGAPS track forecast and the actual (best) track of a storm as shown in Fig. 11. Both the NOGAPS forecast and best-track positions are known for the dependent sample used to develop the regression equations. These best-track positions represent the desired forecast positions after the modification of the NOGAPS forecast positions. Thus, the predictands are the zonal and meridional displacements that are to be added to each of the NOGAPS forecast positions (12, 24, 36, 48, and 72h). Because the 60-h NOGAPS forecast positions were not archived in the data set, a total of 10 regression equations for the five zonal and five meridional adjustments will comprise the desired set of predictands. Separate sets of predictands will be defined for NOGAPS track forecasts in all synoptic pattern/regions for which an adequate sample is available to derive stable regression equations.

2.   Predictors

The outcome of the forward (forecast) positions and backward-extrapolated positions of the first three (12, 24, and 36-h) forecast positions is a series of 12-h positions from -36 to +72 hrs as shown in Fig. 12. Line segments between these positions represent displacement vectors that can be used as predictors. These were converted to zonal and meridional displacements, which distinguish between different types of NOGAPS predicted tracks that are to be improved by statistical adjustments. To this set of predictors derived from the forecast track are added the initial latitude, longitude, intensity, and Julian date. A complete description of predictands and predictors is given in Table 1.

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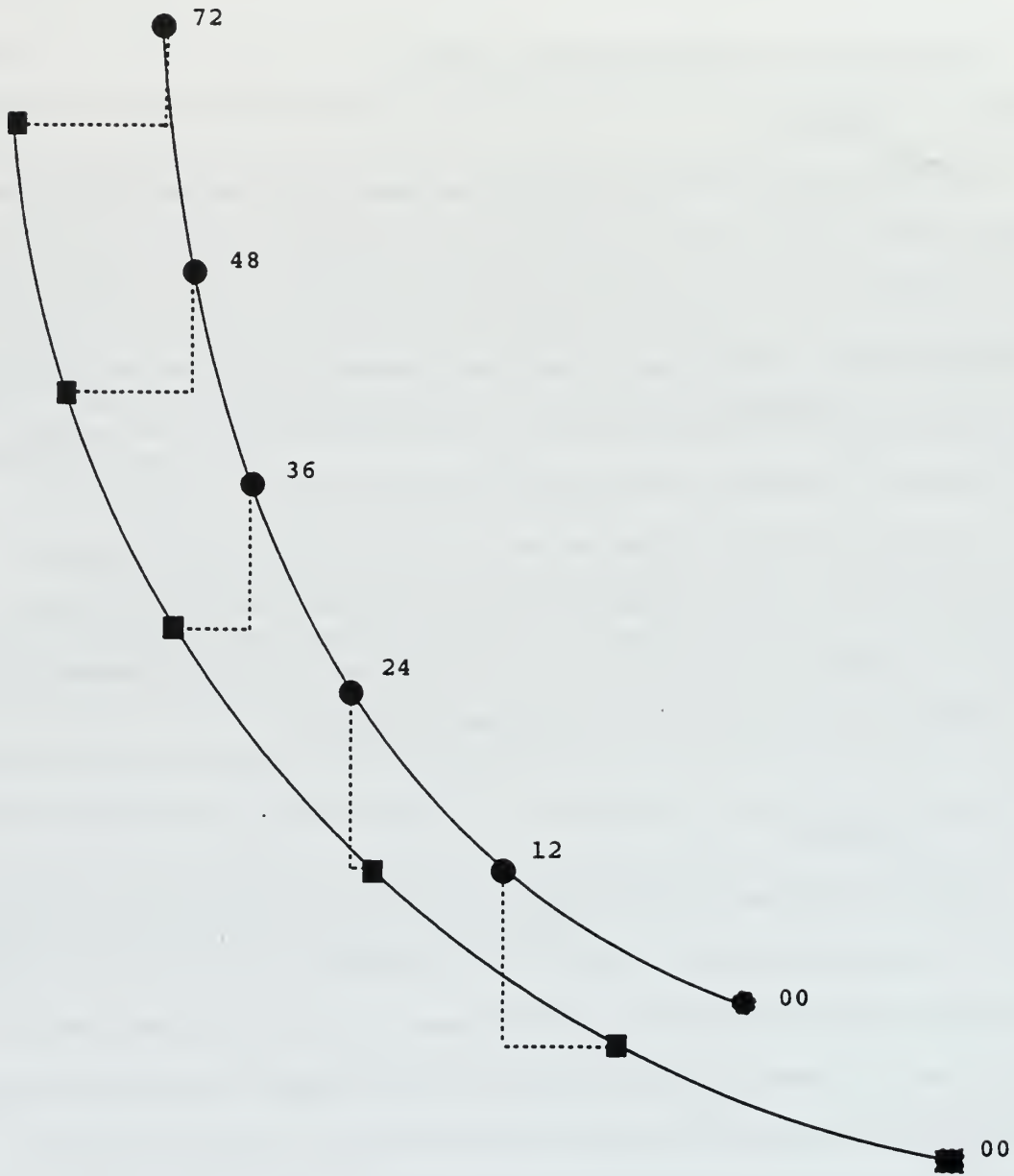
Figure 11. Schematic of the 10 predictands, which are the zonal and meridional displacements necessary to adjust the NOGAPS forecast track (circles) to the best track (squares).
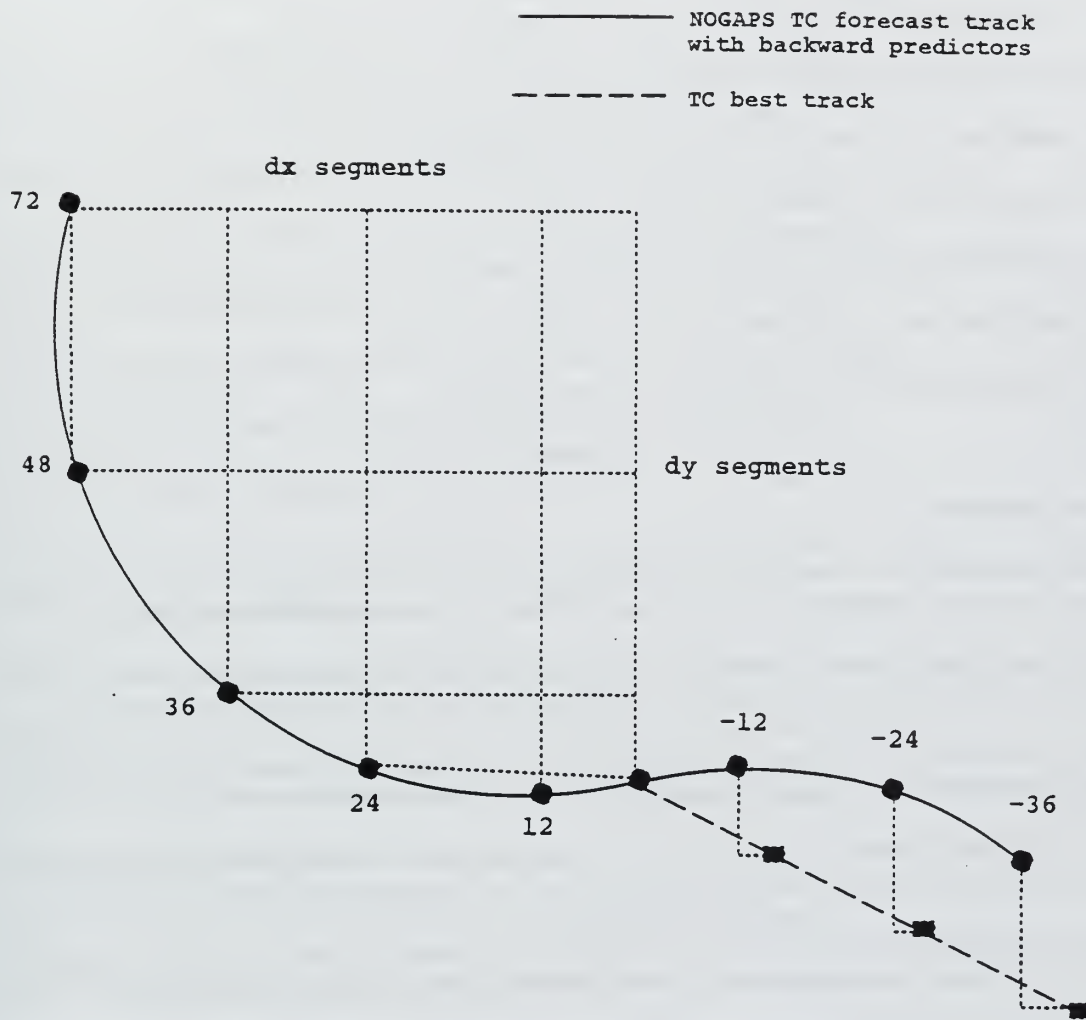
Figure 12. Schematic of the forward predictors, which are the zonal and meridional components of displacements between the NOGAPS 00-, 12-, 24-, 36-, 48-, and 72-h forecast positions, and the backward extrapolated positions at -12, -24, and -36 h that are compared as zonal and meridional components to the best-track positions (boxes).

Table 1. Descriptions of Predictands and Predictors for modifying the NOGAPS TC track forecasts

Predictands

T12dx = zonal correction to NOGAPS T12 forecast position

T12dy = meridional correction to NOGAPS T12 forecast position

T24dx = zonal correction to NOGAPS T24 forecast position

T24dy = meridional correction to NOGAPS T24 forecast position

T36dx = zonal correction to NOGAPS T36 forecast position

T36dy = meridional correction to NOGAPS T36 forecast position

T48dx = zonal correction to NOGAPS T48 forecast position

T48dy = meridional correction to NOGAPS T48 forecast position

T72dx = zonal correction to NOGAPS T72 forecast position

T72dy = meridional correction to NOGAPS T72 forecast position

Predictors

backward predictors

b0012dx = zonal difference between the -T12 position and the corresponding position on the TC best track. -T12 position obtained by changing the sign of the T12 forecast position (backward extrapolation)

b0012dy = meridional difference between the -T12 position and the corresponding position on the TC best track. -T12 position obtained by changing the sign of the T12 forecast position (backward extrapolation)

b0024dx = zonal difference between the -T24 position and the corresponding position on the TC best track. -T24 position obtained by changing the sign of the T24 forecast position (backward extrapolation)

b0024dy = meridional difference between the -T24 position and the corresponding position on the TC best track. -T24 position obtained by changing the sign of the T24 forecast position (backward extrapolation)

b0036dx = zonal difference between the -T36 position and the corresponding position on the TC best track. -T36 position obtained by changing the sign of the T36 forecast position (backward extrapolation).

b0036dy = meridional difference between the -T36 position and the corresponding position on the TC best track. -T36 position obtained by changing the sign of the T36 forecast position (backward extrapolation)

forward predictors

f0000dx = zonal difference between the NOGAPS T00 position and the corresponding position on the TC best track

Table 1. (continued)

forward predictors, continued

f0000dy = meridional difference between the NOGAPS T00 position and the corresponding position on the TC best track

f0012dx = zonal difference between T00 and NOGAPS T12 forecast positions

f0012dy = meridional difference between T00 and NOGAPS T12 forecast positions

f0024dx = zonal difference between T00 and NOGAPS T24 forecast positions

f0024dy = meridional difference between T00 and NOGAPS T24 forecast positions

f1224dx = zonal difference between NOGAPS T12 and T24 forecast positions

f1224dy = meridional difference between NOGAPS T12 and T24 forecast positions

f0036dx = zonal difference between T00 and NOGAPS T36 forecast positions

f0036dy = meridional difference between T00 and NOGAPS T36 forecast positions

f1236dx = zonal difference between NOGAPS T12 and T36 forecast positions

f1236dy = meridional difference between NOGAPS T12 and T36 forecast positions

f2436dx = zonal difference between NOGAPS T24 and T36 forecast positions

f2436dy = meridional difference between NOGAPS T24 and T36 forecast positions

f0048dx = zonal difference between T00 and NOGAPS T48 forecast positions

f0048dy = meridional difference between T00 and NOGAPS T48 forecast positions

f1248dx = zonal difference between NOGAPS T12 and T48 forecast positions

f1248dy = meridional difference between NOGAPS T12 and T48 forecast positions

f2448dx = zonal difference between NOGAPS T24 and T48 forecast positions

f2448dy = meridional difference between NOGAPS T24 and T48 forecast positions

f3648dx = zonal difference between NOGAPS T36 and T48 forecast positions

f3648dy = meridional difference between NOGAPS T36 and T48 forecast positions

f0072dx = zonal difference between T00 and NOGAPS T72 forecast positions

f0072dy = meridional difference between T00 and NOGAPS T72 forecast positions

Table 1. (continued)

forward predictors, continued

f1272dx = zonal difference between NOGAPS T12 and T72 forecast positions

f1272dy = meridional difference between NOGAPS T12 and T72 forecast positions

f2472dx = zonal difference between NOGAPS T24 and T72 forecast positions

f2472dy = meridional difference between NOGAPS T24 and T72 forecast positions

f3672dx = zonal difference between NOGAPS T36 and T72 forecast positions

f3672dy = meridional difference between NOGAPS T36 and T72 forecast positions

f4872dx = zonal difference between NOGAPS T48 and T72 forecast positions

f4872dy = meridional difference between NOGAPS T48 and T72 forecast positions

additional predictors

initial latitude

initial longitude

initial intensity

Julian date

end Table 1

The backward extrapolation process used in this study was first employed by Peak and Elsberry (1982), and is schematically represented in Fig. 13. The major benefit of the backward extrapolation of the NOGAPS forecasts is not to extend the lengths of the characteristic tracks. Rather, the line segments connecting the backward positions at -12, -24, and -36 h with the known past track positions at the corresponding times are used to define the backward predictors (see Table 1). These predictors are very valuable because they contain information regarding the peculiar environmental and TC conditions for each forecast. Those situations that have large backward predictors are cases in which the NOGAPS forecast over the first 36 h will likely depart markedly from a persistence-type forecast based on the past 36-h motion. The hypothesis is that such NOGAPS forecasts will require larger statistical adjustments. By contrast, situations with only small backward predictors are expected to require smaller adjustments to the NOGAPS forecasts because the initial predicted motion agrees well with a persistence-type forecast. Although the most likely contribution to large backward predictors is a poor initial specification of the environmental steering flow so that the NOGAPS-predicted track departs significantly from the recent storm motion, an incorrect TC outer circulation in the NOGAPS analysis may also cause a track deviation.

The forward-only predictors may be interpreted as characterizing a particular type of track, e.g., more poleward or more westward than average for that synoptic pattern/region. Those forecast situations in which NOGAPS has a large forecast error involve track direction changes during the 72-h forecast, especially if an observed track change is not forecast, or a forecast track change is not observed.

The regression equations developed for this study are generated using a variation of stepwise regression techniques used by Chen *et al.* (1998). In the stepwise regression approach, the first predictor selected explains the greatest amount of variance in the predictand. Subsequent predictor selection is based on the highest partial correlation given the inclusion of the prior selected predictor(s). As more predictors are added one at a time, the increase in explained variance from the additional predictor may become
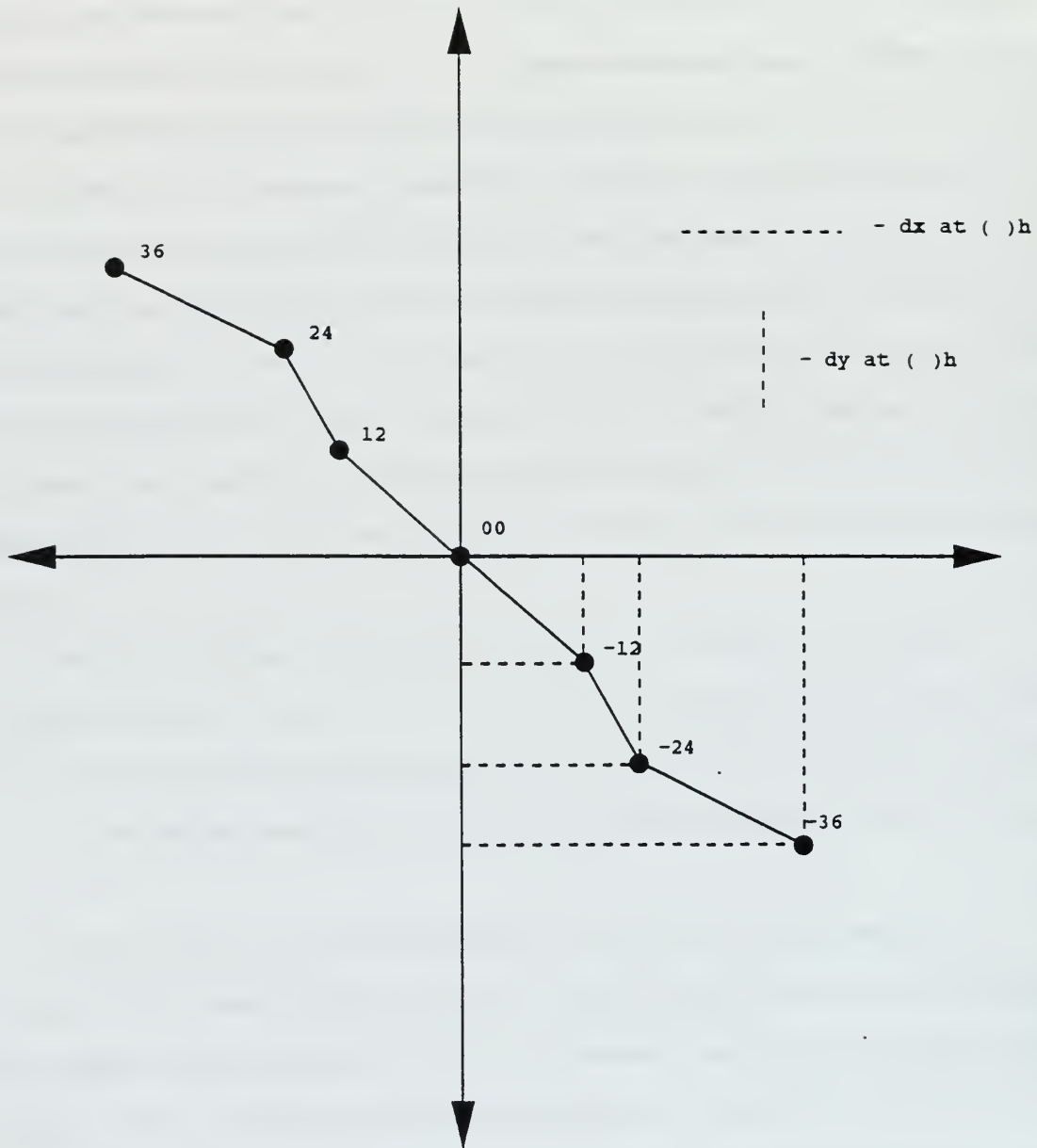
Figure 13. Illustration of backward extrapolation technique (After Peak and Elsberry 1982).

erratic. With a fairly limited set of NOGAPS forecasts on which to develop the regression equations, and a total of 46 predictors, a major concern is not to allow the technique to select too many predictors. That is, it is possible that the development sample may be fit overly well if too many predictors are allowed to enter the stepwise regression.

An option in the stepwise regression technique is exercised to allow removal of prior predictors after the entry of each new predictor. This sometimes occurs with either the forward or backward predictors in Table 1. Notice that these predictors are somewhat linearly related. For example, the 00-24 h displacements are almost double the 00-12 h displacements in a persistent-track regime. Similarly, the backward predictors at 24 h may be nearly double the backward predictors at 12 h if the past motion has been steady. Allowing removal of prior predictors appears to handle linearity in the predictors.

Various predictor-cutoff tests were conducted by examining the percentage improvement of modified NOGAPS TC track forecasts relative to unmodified tracks. Although the primary factor was mean track forecast error improvement, the standard deviations of the errors were also compared. These cutoff tests must be conducted with independent samples. In this study, an independent sample was generated by setting aside every third case in each data base used. The data base is discussed in detail in the next section.

Initial tests were conducted allowing the statistical package default criterion for terminating predictor selection. Results of these tests showed effects of over-fitting caused by selection of too many predictors. Various upper limits of predictor selection were tested. Best results were obtained by limiting the regression routine to five steps, which may result in selection of only 3-5 predictors if the predictor removal option is exercised.

B.   DATA BASE

Several crucial decisions had to be made concerning the number of and nature of the cases for which regression equations could be developed. Synoptic pattern/region characterizations for the 4017 cases in the 1989-1996 data base utilized by CEB98 were theoretically available for this study. Unfortunately, a large number of the cases had limited applicability in this study, for reasons that will be discussed below.

Calculations of the predictands and predictors in Table 1 requires an archive of both the NOGAPS TC track forecast positions and the TC best-track positions, as determined by JTWC. The first significant limitation noted in the NOGAPS data set concerns the actual NOGAPS starting position (00-h) for the forecast. A brief overview of the process that generates the starting position is essential to understanding the nature of this limitation.

Once the forecasters at JTWC (or another forecast center) have determined that a tropical depression has reached storm intensity, they generate a so-called Combined Automated Response to Query (CARQ) message and transmit it to FNMOC prior to the synoptic time. The CARQ message provides an expected (extrapolated) position for a TC at the synoptic time, so that it can then be automatically inserted into the NOGAPS analysis during its next scheduled run. It is this CARQ position that locates the center for the synthetic observations discussed in Chapter I.B. This starting position and the corresponding synthetic observations will be blended with the 6-h NOGAPS forecast through the MVOI process, also discussed in Chapter I.B.

As noted earlier, the combination, or blend, of all real observations, NOGAPS synthetic observations based on the JTWC CARQ message, and a 6-h forecast, or first-guess, during the MVOI step often produces a starting position for the NOGAPS track forecast that differs (at times significantly) from the actual starting position of the TC at the synoptic time, or the extrapolated position provided up to two hours earlier in the CARQ message. Unfortunately, the 00-h position in the NOGAPS forecast track has not

been archived, because it had been assumed that all forecast guidance would begin at the 00-h warning position. This is not true for NOGAPS (or other dynamical models), because of the blending aspect of the MVOI.

The CARQ positions, which are extrapolated JTWC warning positions, are often based on satellite interpretation. Determination of TC positions from satellite imagery may be inaccurate when cirrus shields mask the true center of the TC wind structure. The JTWC tropical cyclone warning messages that are archived in the data set include the revised position from the CARQ synoptic time, and thus are based on later information. Because it is transmitted some time (up to 2 hours) after the NOGAPS analysis and forecast of the TC track has already begun, based on the CARQ position, the warning position also does not represent the NOGAPS starting position. While these warning positions may be more accurate than the CARQ positions, having been determined through additional study of observations and satellite imagery, they are of limited utility for this study due to their disconnect from the NOGAPS forecast track. The best-track positions that are considered to be "truth" in this study are determined in post-storm analysis that has the benefit of all later center fixes to help determine the likely accuracy of the fixes available in real time.

All of the 1989-1996 archived tracks contain these uncertainties in the NOGAPS starting position of the TC. One potential solution to this limitation of the data set would be to expand on the backward extrapolation technique of Peak and Elsberry (1982), which is described in Table 1 when developing the regression equations discussed earlier. Given accurate 12-, 24-, and 36-h NOGAPS forecast positions, backward extrapolation could be performed to estimate the NOGAPS starting position.

Extrapolation of the initial NOGAPS position can not be done accurately for the 1989-1991 cases and some 1992 cases, which do not have 12-h and 36-h positions archived in the data base, as this would be a 24-h extrapolation from only three NOGAPS forecast positions. In addition, the lack of 12- and 36-h positions from 1989-1992 poses a second significant limitation to the data set. A reasonable estimate of these positions could have been interpolated if the 00-h NOGAPS starting position had been available

along with the 24- and 48-h forecast positions. However, the lack of an accurate NOGAPS starting position means the 12-h position would not be an interpolation, but an extrapolation from the 24 -, 48 -, and 72-h NOGAPS positions. Although the 36-h position interpolation could be done, it would not be as accurate as if the 00-h NOGAPS position had been available. Thus, it was decided to limit this study to that portion of the data set that had 12-h and 36-h positions available – namely, the 2500 tracks from 1992-1996.

The impact of extrapolating a 00-h NOGAPS position versus using the 00-h warning position will be quantified in Chapter III.B. A set of regression equations will be developed using the CARQ position as the 00-h NOGAPS position in the calculation of the predictors in Table 1. A second set of regression equations will then be developed with NOGAPS starting positions obtained by extrapolating a 00-h position from the 12-, 24-, and 36-h positions through the use of a quadratic function. A comparison of the accuracies of these two equations will illustrate the impact of the interpolated NOGAPS starting positions, versus having to rely on the archived warning positions in the calculation of the predictors.

The 152 TCs during 1992-1996 have been characterized into synoptic pattern/region combinations from 12-h NOGAPS analyses at 0000 UTC and 1200 UTC. A lower TC intensity limit of 25 kt (versus 35 kt for many dynamical model studies) was imposed to obtain the largest possible sample sizes. Notice that intensity is one of the predictors in Table 1. It is well known (Elsberry 1995) that track forecast errors are larger for weaker TCs than for the typhoon stage. It is important to try to improve the NOGAPS track forecasts for these weaker TCs because JTWC must issue warnings on these TCs, and they need improved NOGAPS guidance.

Once the 152 TCs had been stratified into synoptic pattern/region combinations, selection criteria had to be developed to determine the number of usable samples (track forecasts) in each combination. Different potential samples for both the development and validation of the regression equations may be formed by inclusion of all TCs in a pattern/region at the initial time that then remain in that pattern/region

for at least $T = 0, 12, 24, 36, 48,$ or 72 h. As T increases, the sample size decreases because the TC inclusion criterion becomes more stringent. However, longer portions of these tracks will have similar characteristics, as the inclusion of the dissimilar post-transition tracks will be limited to the times beyond T hours (Chen *et al* 1998).

Calculation of the backward predictors in Table 1 requires NOGAPS positions for the first 36 h of the forecast for backward-extrapolation and comparison with the past 36-h positions from the TC best track. For the predictands, the NOGAPS forecast positions that verified beyond the end of the JTWC best track were eliminated. The sole exception to this criterion was the inclusion of a 36-h forecast position for all TCs, even those in which the TC dissipated within 24 h of the forecast. This 36-h forecast position was included to allow the calculation of a backward-extrapolated 36-h predictor. Even if the TC dissipated after, say, 36 h, the 12- and 24 h NOGAPS forecasts need to be adjusted, and the available predictors should include all existing NOGAPS forecast positions to calculate the forward predictors in Table 1. A more common problem is the loss of the NOGAPS forward predictors when the tracking routine can no longer follow a weak vortex out to 72 h. In these cases, the forward predictors that involve NOGAPS forecast predictors beyond the end of the available track positions are not available to the regression equation development, which is referred to as the "missing predictor" problem.

The multiple linear regression techniques discussed in Section A of this chapter were applied to both the entire data set, and to each pattern/region combination (subset) for which a sufficient sample size existed (see Results in Chapter III). The final limitation of the data set was noted immediately following initial development of the regression equations. Approximately half of the cases archived in the data set were NOGAPS forecasts for initial times of 06 and 18 UTC. However, these "forecasts" do not represent any new or independent NOGAPS model integration. Rather, they are merely extended and re-labeled forecast positions from the previous NOGAPS model run, and are used by JTWC forecasters as an initial forecasting tool. These offtime "forecasts" were both linearly dependent on the 00- and 12-h NOGAPS model forecasts, and a significant fraction contained erroneous data points. Because introduction of these

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cases degraded the regression process significantly, these 06 and 18 UTC forecast cases are removed. Thus, regression equations are developed using only the 00 UTC and 12 UTC forecasts. The sample sizes for deriving and testing the regression equations for both the entire, undivided data set, and for each pattern/region subset that is tested are given in Table 2. Notice that the largest category of "All Cases" with at least one forecast in the pattern/region has only 1187 cases, rather than the 2500 initially available. Most of this decrease is the omission of the 06 UTC and 18 UTC forecasts.

Table 2. Sample sizes for developing and testing regression equations with the criterion that the TCs remained in the pattern/region (see Figure 2 for acronym definitions) for at least T hours.

Time in pattern/region (in hours)

Pattern/ Region	00	12	24	36	48	72
All Cases	1187					
S/DR	630	328	266	216	176	106
P/PO	299	134	90	66	48	31
Other Cases	258					

III.   RESULTS

Application and testing of the regression equations progressed in a sequence designed to address two main goals. The basic goal was to test the hypothesis that sets of regression equations stratified by the Systematic Approach synoptic pattern/regions would provide more accurate NOGAPS track adjustments. The second goal was to develop a set or sets of regression equations that had maximum utility for operational forecasters, given the sample of 2500 NOGAPS forecasts in the 1992-1996 data base that was already limited by key factors such as the CARQ position problem and the questionable utility of the 06 and 18 UTC forecasts as discussed in Chapter II. The discussion below will show that the two goals are directly related.

A.   APPLICATION OF THE REGRESSION EQUATIONS TO FULL PREDICTOR DATA BASE

Initial development of the regression equations was conducted on a "complete" data set prior to stratifying the data into pattern/region combinations. This "all cases" set of regression equations (hereafter PR/ALL) creates a control case to compare with the sets for specific synoptic pattern/region combinations. In addition, questions concerning the effects of a limited sample of NOGAPS forecasts could be addressed with the largest possible PR/ALL sample before subsamples are attempted.

An immediate obstacle to development and testing of regression sets with the forward and backward predictor sets in Table 1 is the problem of handling missing predictors. First, the expected utility of the backward predictors from the EF and Peak and Elsberry (1982) studies led to the restriction that at least a 36-h NOGAPS forecast was necessary. However, it is possible that statistical post-processing of a 12-, 24-, or 36-h NOGAPS track forecast may involve predictors that depend on 48- and 72-h NOGAPS forecast positions (see list in Table 1). Although the stepwise regression algorithm can handle missing predictors during the development stage, it is not clear how to apply such equations.

Based on advice from Dr. Pat Harr, an interim step is to first require that the development data base contain full predictor entries to determine if potentially missing 48- and 72-h predictors would indeed be selected. Although this requirement further reduces the sample sizes by about 15-20%, it ensures that the regression equation sets could always be applied to both the development (2/3) and test (1/3) samples, as all predictors are available. The procedures to address the missing predictor problem will be discussed later.

A significant problem was encountered immediately upon applying the first PR/ALL equation sets. The nature of the problem, and its solution, are illustrated in Fig. 14. As discussed in Chapter II.B, it was anticipated that stable regression equations may only be developed for pattern/region combinations that contained a sufficient number of usable cases. That is, it was anticipated that the sample sizes of a number of pattern/region combinations might be too small for development of stable regression equations, especially for longer forecast intervals. This topic is discussed in more detail in Section D of this chapter.

It had been anticipated that the sample sizes for the S/DR, P/PO, and certainly the PR/ALL, data sets would be adequate to allow the development of stable regression sets to post-process the NOGAPS track forecasts. As shown in Fig. 14, this was not the case. The top line of Fig. 14 is the mean forecast track error for all unadjusted NOGAPS TC forecasts during 1992-1996. The line connecting the boxes represents the mean track forecast error for the adjusted NOGAPS track forecasts with an initial set of regression equations that are developed with a 2/3 dependent sample. While a large track forecast improvement is noted during the early forecast intervals, the crossover between 48 h and 72 h indicates a degradation of the NOGAPS forecasts after 48 h. That is, it represents an "adjustment" that produces greater error than an unadjusted forecast, which may be associated with an inadequate set. Whereas this degradation at 72 h occurs even during development of regression equations using the PR/ALL data set, adjusted NOGAPS 72-h forecasts are even more degraded when tested with the 1/3 independent sample (not shown).
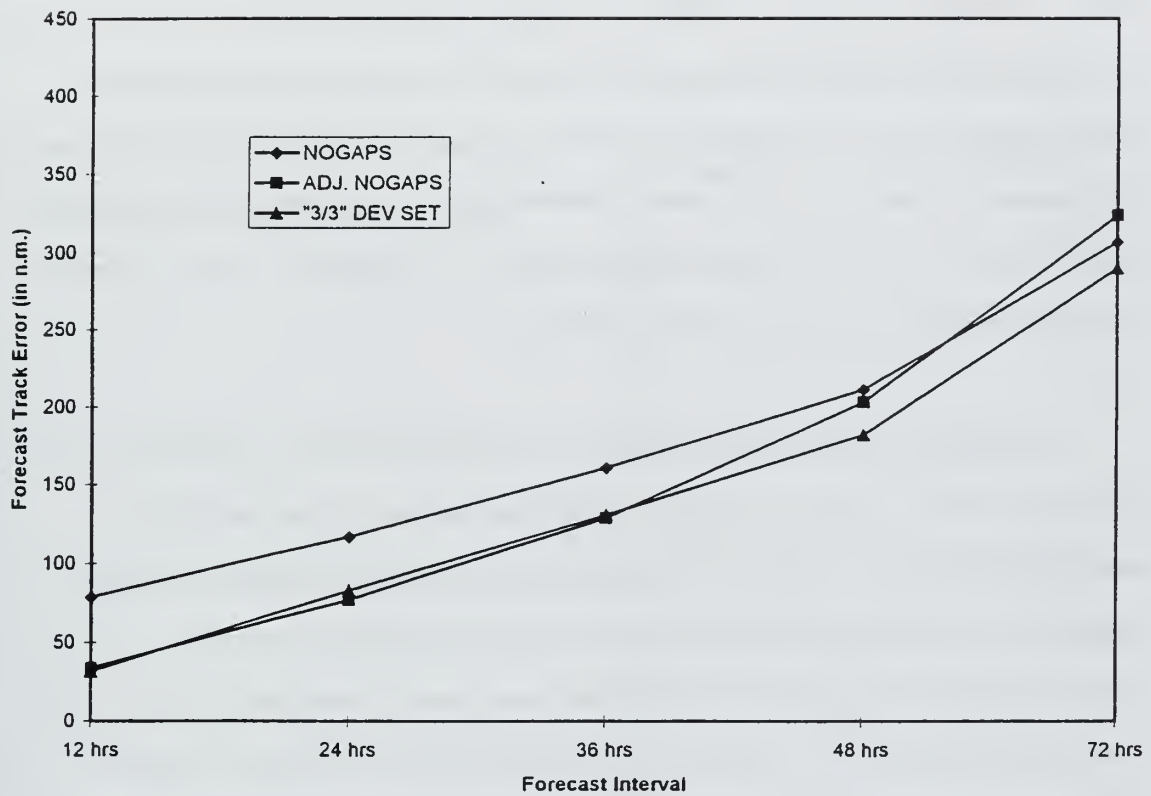
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Figure 14. NOGAPS track forecast errors for the sample of all pattern/region combinations (diamonds) and after statistical adjustment derived from a 2/3 development sample (boxes) or the full 3/3 development sample (triangles) of the combined (PR/ALL) synoptic pattern/regions. These statistical adjustments are for the full predictor samples.

The origin of the difficulty in developing accurate regression equations at longer time intervals is illustrated by the mean values of the predictands as a function of forecast interval (Fig. 15). The mean values of the required adjustments to the 12-h NOGAPS forecasts are small because both positive and negative zonal and meridional adjustments that are required in individual cases tend to offset in the mean. Because such 12-h errors arise from a poor initial position and initial track direction/speed, the 00-h position offset predictors and backward predictors are quite effective in adjusting the NOGAPS 12-h forecasts. Although the systematic NOGAPS errors increase with forecast interval, these errors are less and less related to initial track direction/speed problems, and more to do with numerical model biases. Considering that the mean 72-h adjustment in the PR/ALL sample is about 45 n mi relative to a typical displacement of 700-1000 n mi, the adjustment is relatively small. The degradation of the adjusted 72-h NOGAPS track forecast with the 2/3 dependent sample in Fig. 14 is attributed to a too-small sample to describe the model bias with the given predictors in Table 1.

One solution to this problem is to obtain the necessary larger samples by transferring into the development set the 1/3 of the cases set aside as an independent test set. The disadvantage that an independent set is then not available will be addressed later. As indicated by the line connecting the triangles in Fig. 14, NOGAPS track forecast improvements are now obtained for the entire 72-h forecast interval. These results of using this "3/3" development sample serve to validate the use of the regression equations given sufficient cases. Whereas the 2/3 development sample for PR/ALL has 508 cases at 72 h, the 3/3 development sample has 761. This indicates how critical sample size is for developing accurate adjustments to the NOGAPS 72-h forecasts. Given this sample size requirement for the combined sample of all pattern/regions, it is anticipated that the sample size difficulty may also plague the individual pattern/region developments. Nevertheless, a baseline set of equations had been developed. With this control set in place, testing of subsets could begin.
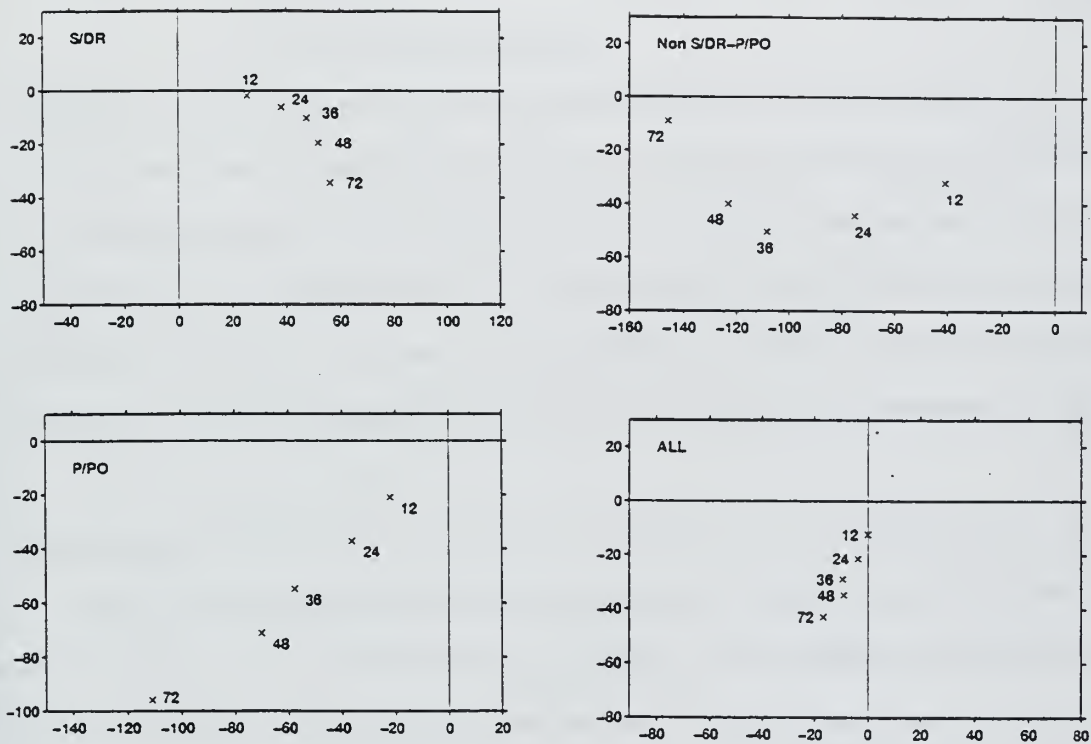
Figure 15. Mean positions of the unadjusted NOGAPS track forecast errors (n mi) from 12 h through 72 h relative to the actual TC position (0,0) for S/DR, P/PO, other than S/DR or P/PO, and all TCs.

B. **APPLICATION OF THE REGRESSION EQUATIONS TO THE FULL PREDICTOR DATA SET WITH EXTRAPOLATED NOGAPS STARTING POSITIONS**

One hypothesis of this thesis is that use of the CARQ position as the initial NOGAPS position would result in degraded adjustments of the early portions of the NOGAPS tracks. The limitations in the sample arising from the failure to archive NOGAPS starting positions are discussed in detail in Chapter II.B. As noted in that section, one possible method for reducing uncertainties in the NOGAPS starting position is to apply a backward extrapolation technique. In this section, an alternate initial 00-h NOGAPS position is obtained by backward extrapolation from the NOGAPS 12-, 24-, and 36-h forecast positions. Given these three NOGAPS positions, Mark Boothe applied quadratic equations to extrapolate the 00-h position.

New regression equations are then developed with the full-predictor data set, as in Chapter III.A above. The results of this test are shown in Fig. 16. It is somewhat surprising that the extrapolated NOGAPS initial starting position results in no performance improvement over regression equations developed using the CARQ position as the 00-h position. A possible explanation is that the 00-h offset predictors and the backward predictors (see Table 1) provide characteristics of the early TC track behavior that allow the regression equation to lessen the impact of not having archived the NOGAPS 00-h position.

Given these initial results, no further efforts were made to develop or test regression equations using extrapolated starting positions. Nevertheless, it is recommended that the actual 00-h NOGAPS position, which is already available from the vortex tracking algorithm, be archived and used in place of the CARQ position. It seems reasonable that an inaccurate initial NOGAPS position will cause an offset in the entire early track forecast. Thus, it would be advisable to have the actual initial NOGAPS position available. A large sample with the archived initial position would have to be accumulated before the new regression equations could be developed.
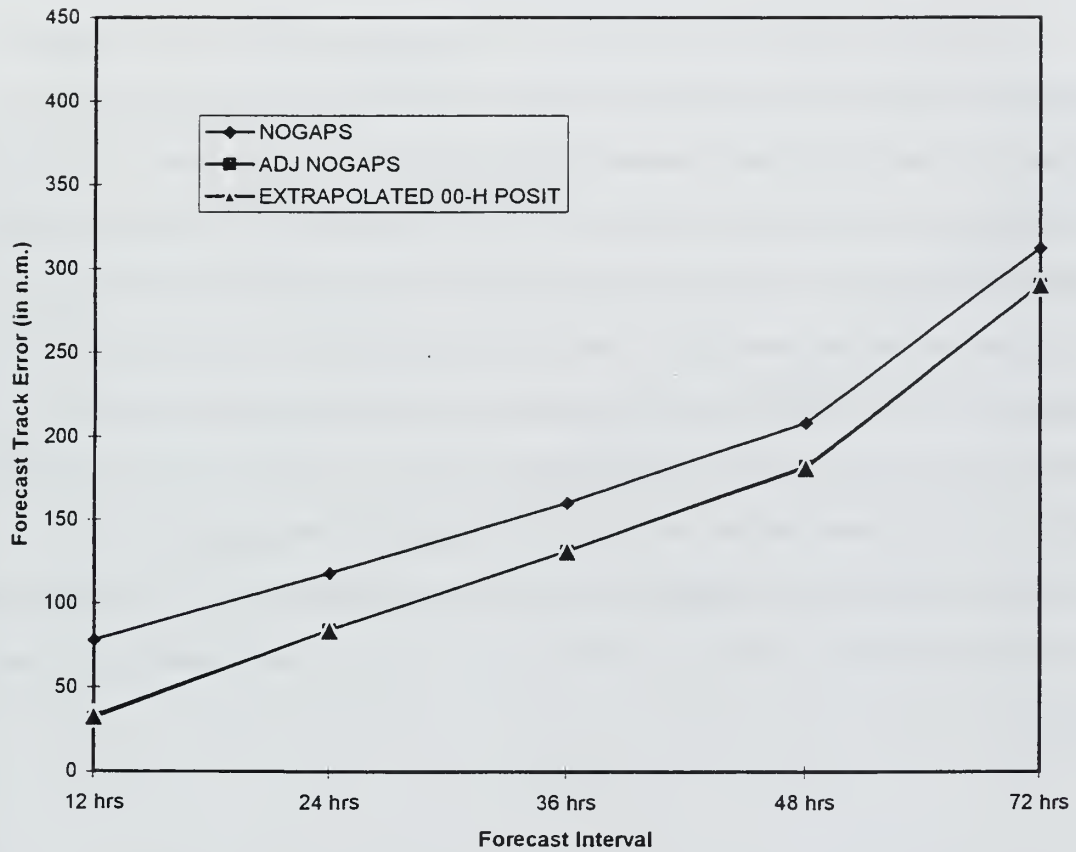
Figure 16. NOGAPS track forecast errors as in Fig. 14 with the full 3/3 development sample of PR/ALL synoptic pattern/regions, except using an extrapolated NOGAPS starting position, rather than the CARQ position. The 2/3 development sample is not shown.

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C.   MISSING PREDICTORS

As noted in Chapter II.B and Chapter III.A, the NOGAPS TC vortex tracker may lose a weak or poorly developed storm, which leads to an incomplete track forecast. Thus, a portion (about 15-20%) of the NOGAPS forecasts lacked some of the forward predictors that involve the 48- and 72-h positions. The question of how to apply the regression equations in these missing predictor cases is an important one for operational utility.

To avoid the missing 48- and 72-h NOGAPS track prediction problem, a new set of regression equations is developed in which all predictors in Table 1 involving the 48- and 72-h NOGAPS forecast positions are omitted. This reduces the number of predictors from 46 to 24, and increases the development sample (the sample sizes are listed in Table 2) by the 15-20% of the cases that had been omitted in the full-predictor sample used above. Because of this larger sample, the unadjusted NOGAPS track errors in Fig. 17 are slightly different from those in Fig. 14 with the full predictor sample. It is indeed fortunate that omitting the 48- and 72-h forward predictors resulted in an almost identical adjusted NOGAPS track forecast performance, with perhaps a slight improvement in the 00-36 h equation set. That is, these less-restrictive equations enhance the operational utility of these techniques to the forecaster. In this circumstance, the equations can be applied to weak or poorly developed TCs for which NOGAPS produces only a 36-h track forecast. It is these sets of "00-36 h predictor" equations that are tested in the following sections.
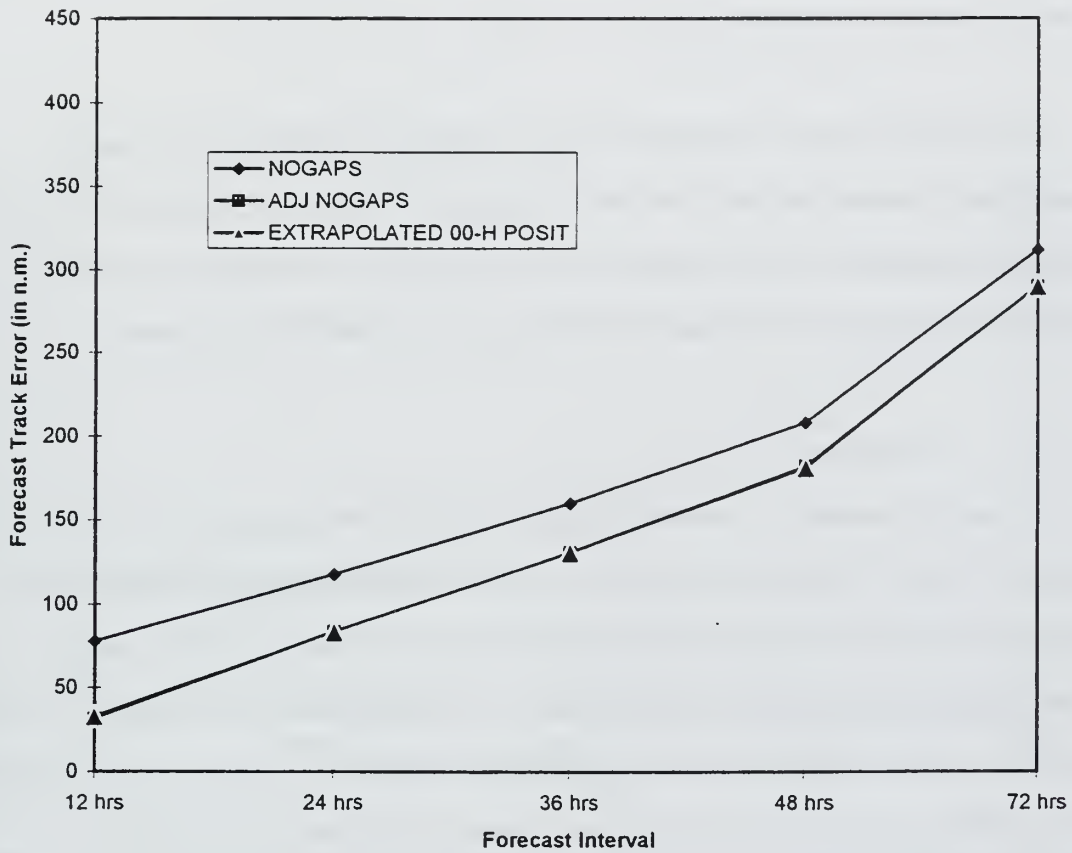
Figure 17. NOGAPS track forecast errors as in Fig. 14, except only the 00-36 h forward predictors (rather than 00-72 h forward predictors) are allowed for the adjusted NOGAPS errors (triangles). This restriction avoids the missing predictor problem and increases the sample size relative to the full-predictor sample in Fig. 14. A 2/3 development sample is not shown.

D. APPLICATION OF THE REGRESSION EQUATIONS TO SELECTED PATTERN/ REGION COMBINATIONS

The main hypothesis of the thesis that NOGAPS statistical adjustments will be more effective if used on samples of similar synoptic pattern/regions may now be tested. It is expected that the regression techniques for deriving a statistical adjustment for the NOGAPS TC tracks would be more accurate because similar tracks occur in the same pattern/region combination.

Given the TCs in three synoptic pattern/region combinations (S/DR, P/PO, and all others), separate regression equations are derived and tested to determine the improvement in the NOGAPS tracks after statistical adjustment to reduce the errors in Fig. 15. As noted above, the equations are developed using only 00-36 h forward predictors and the CARQ position as the initial NOGAPS position.

1. S/DR Cases

Of the 1187 possible 12-h forecast situations with at least a 24-h track history, 630 are in the S/DR combination (Table 2). With the requirement to have large development samples established from the PR/ALL case in Chapter III.A, only regression equations for the T=00 (currently in S/DR) cases are developed. After larger sample sizes are accumulated for the TCs remaining in S/DR for at least 12 h, 24 h, etc, separate regression equation sets might be developed and tested as in the Chen *et al.* (1998) statistical-synoptic technique. The important point is that the only requirement is that the TC is initially in S/DR (something the forecaster will know); the TC may have left the S/DR pattern/region at some time during the 72-h forecast interval (which the forecaster may or may not know).

Since the entire S/DR sample has to be used to develop the regression equations, no independent test sample is available, and the comparison in Fig. 18 is for the development sample. Because the NOGAPS is generally more accurate for TCs in the S/DR pattern/region, the unadjusted NOGAPS errors
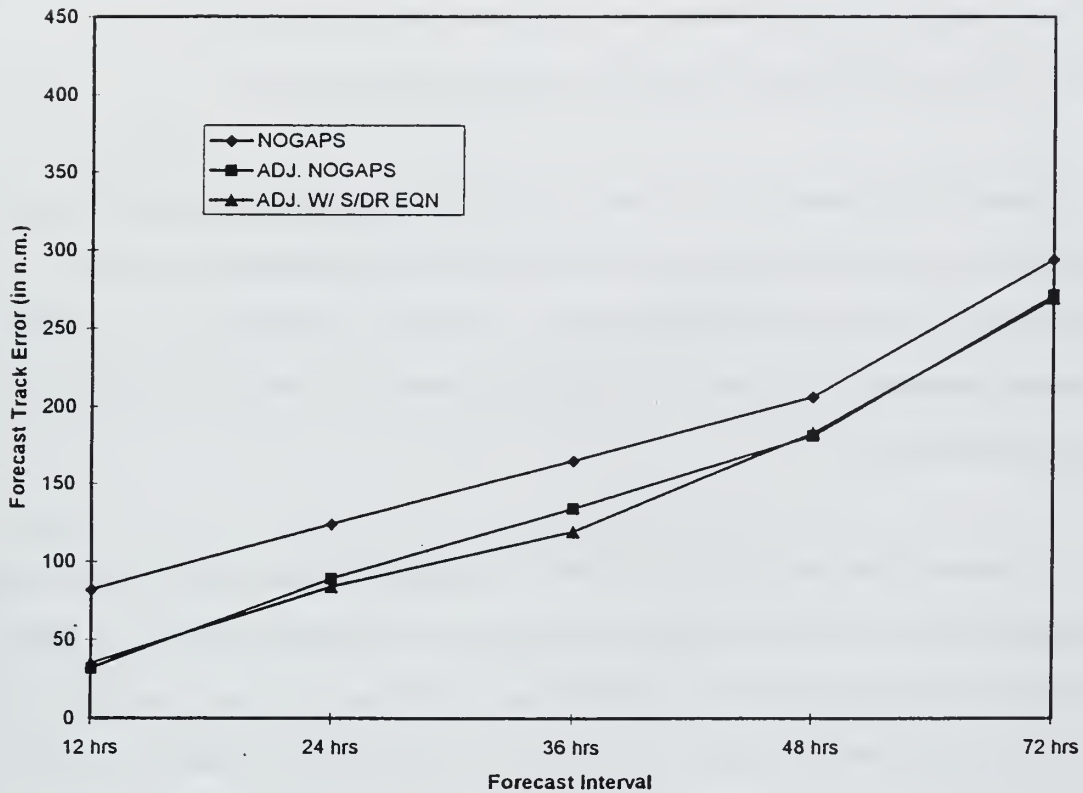
Figure 18. NOGAPS track forecast errors as in Fig. 17, except for a subsample of TCs that are in the S/DR pattern/region combination at the initial time. NOGAPS errors for this subsample are compared with the adjusted NOGAPS errors from regression equations developed from the All (boxes; as in Fig. 17) or separately from the S/DR only (triangles) samples. Only development sample errors are presented as no independent samples are available.

are smaller in Fig. 18 than in Fig. 17, especially at 72 h. Notice that applying the PR/ALL regression equations (as used in Fig. 17) to this subset of S/DR cases at the initial time results in adjusted NOGAPS errors (boxes in Fig. 18) that have a similar improvement as when applied in the ALL sample (Fig. 17). This improvement is 61% after only 12 h, 30% at 24 h, 20% at 36 h, and is further reduced to about 8% at 72 h. Some additional improvement is obtained at 24 h and 36 h from the regression set derived from only S/DR cases (triangles in Fig. 18). However, these improvements may not be significant and must be established with an independent sample, rather than with this development sample.

Given this limited sample of S/DR cases, it is not possible to validate the hypothesis that a statistical adjustment based only on S/DR cases will result in improved performance relative to the adjustment based on TCs in all synoptic pattern/regions. Although this is disappointing, it is an advantage for operational application to have a single set of regression equations rather than one for S/DR cases and for other pattern/regions.

In addition to reduction in the mean NOGAPS track errors, the standard deviations about the mean are also reduced by the statistical adjustment (post-processing). In this subsample of S/DR cases, the standard errors are reduced from 56 to 22 n mi at 12 h, from 101 to 80 n mi at 36 h, and from 200 to 187 n mi at 72 h. This means that the adjusted NOGAPS errors have a smaller spread, as illustrated in Fig. 19.

2. P/PO Cases

Another pattern/region combination with a relatively large sample size for testing is the P/PO pattern/region. If the only inclusion criterion is that the TC is in P/PO for at least $T = 0$ h, 299 usable cases are available (Table 2). As with S/DR, the sample size drops considerably as the inclusion criterion increases to 72 h (i.e., the TC remains in P/PO for the entire forecast period). To maximize the size of the development sample, regression equations are developed only for the $T = 0$ h cases.
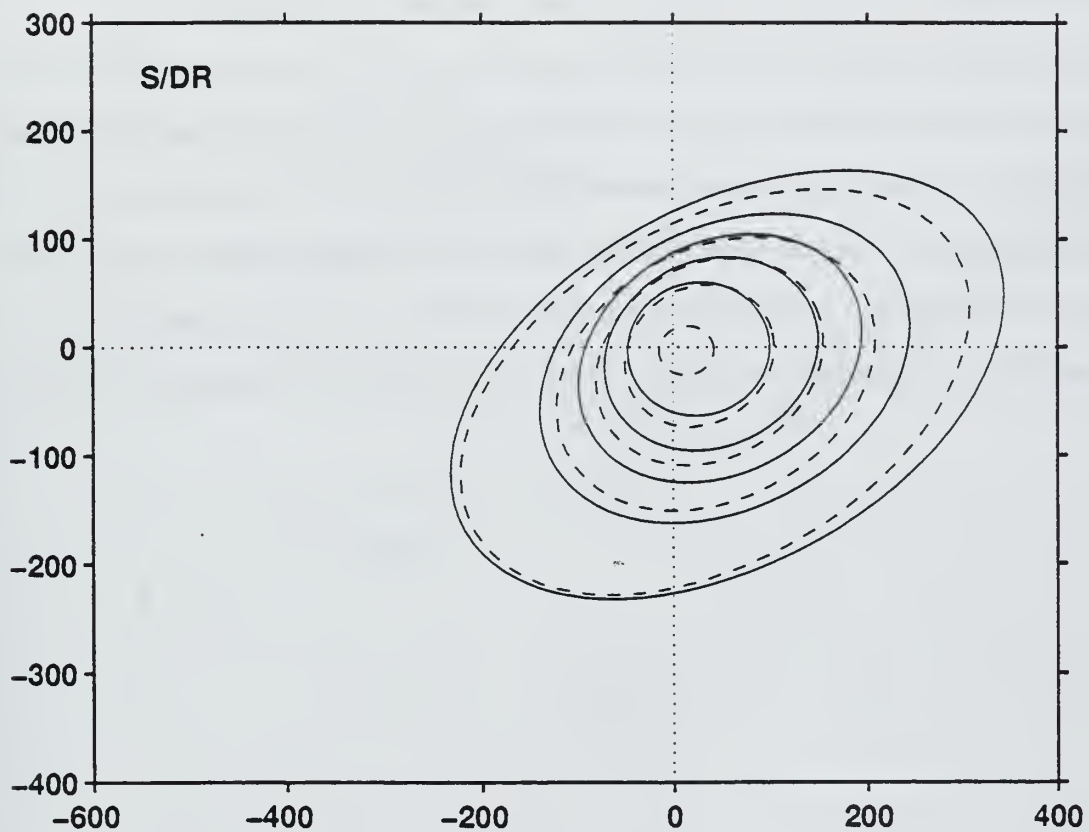
Figure 19. Track forecast error ellipses enclosing 68% of cases at 12 h (innermost), 24 h, 36 h, 48 h, and 72 h (outermost) for unmodified NOGAPS tracks (solid lines) and adjusted NOGAPS tracks (dashed lines) in the S/DR pattern region. Errors are plotted in geographic coordinates with north at the top.

Applying the PR/ALL regression equations (as used in Fig. 17) to this subset of P/PO cases at the

initial time again results in adjusted NOGAPS errors (boxes in Fig. 20) that have a similar improvement as

when applied in the ALL sample (Fig. 17). Whereas the unadjusted NOGAPS errors over 12-36 h are

relatively smaller in these P/PO cases, these errors are somewhat larger than in the ALL sample at 72 h. As

before, significant track forecast improvement is obtained using the PR/ALL regression equations, with

55% at 12 h and a decrease to 6% at 72 h. As above in the S/DR-only cases, only a small additional track

forecast improvement is achieved at 36 h when a new of regression equations is developed from the P/PO-

only sample (triangles in Fig. 20). Since the improvement is small, and this result is based on the

development sample, the hypothesis that a statistical adjustment based only on the P/PO cases will result in

an improved NOGAPS performance relative to the statistical adjustment derived for all pattern/regions can

not be validated. However, this result is advantageous for simplicity of operational application. A

reduction of standard errors is again achieved for the subsample of P/PO cases; reductions are from 71 n mi

at 12 h, from 152 n mi to 119 n mi at 36 h, and from 247 n mi to 224 n mi at 72 h are achieved. As

illustrated in Fig. 21, this results in the adjusted NOGAPS errors having a smaller spread about the mean.
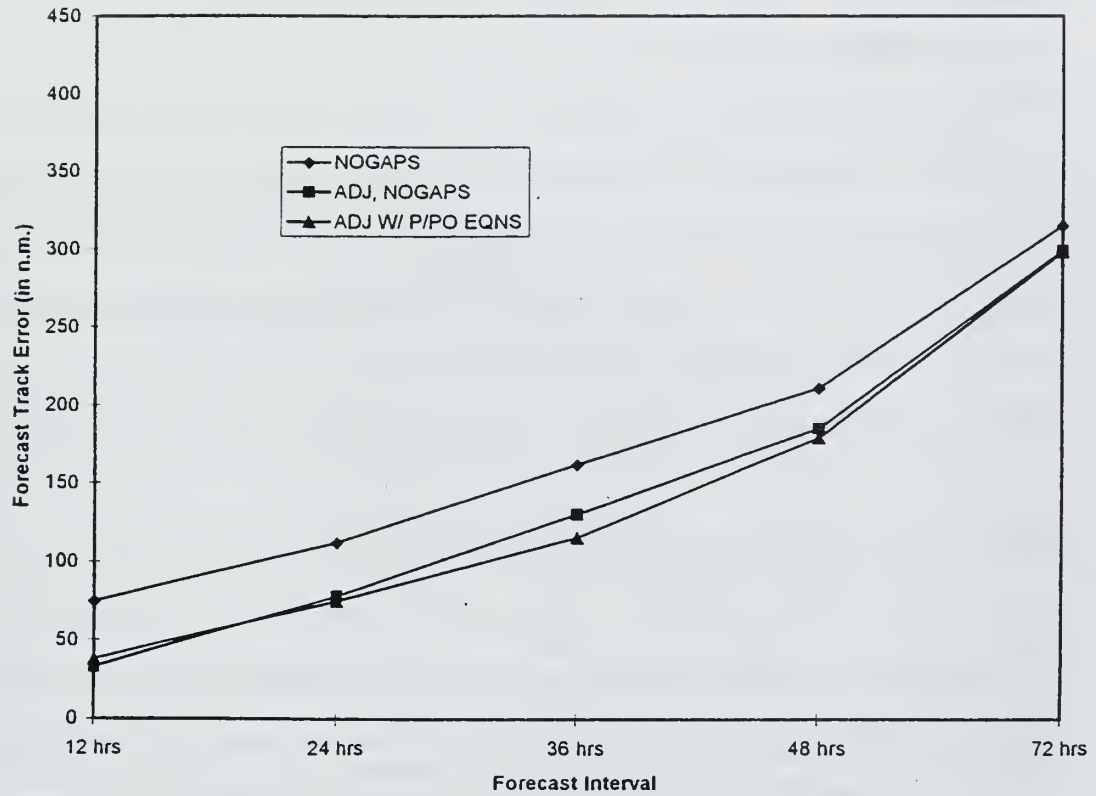
Figure 20. Comparison of unadjusted (diamonds) and adjusted NOGAPS track errors as in Fig. 18, except for the subsample of TCs in the P/PO pattern/region combination.
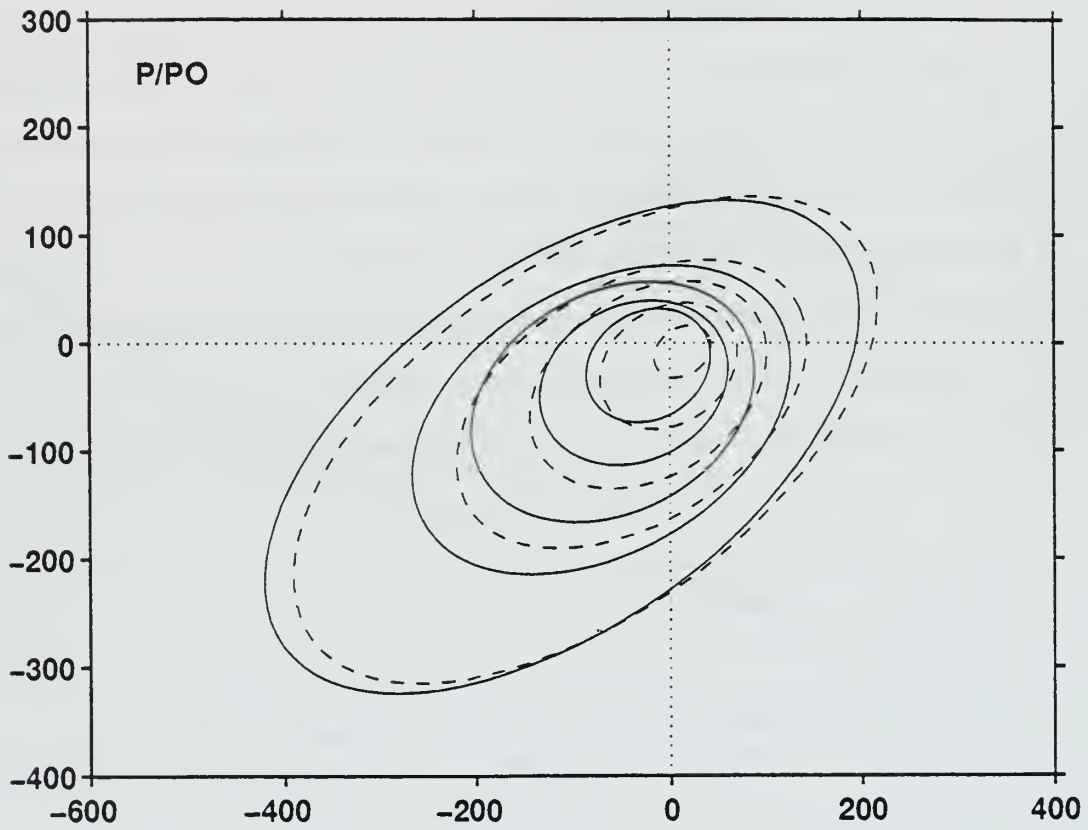
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Figure 21. Error ellipses as in Fig. 19, except for the P/PO pattern/region combination.

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3. All remaining pattern/regions

Because reliable statistical regression requires a large dependent sample, it had been anticipated that the sample sizes of the pattern/region combinations other than S/DR or P/PO might be too small for development of stable regression equations for longer forecast intervals. As discussed in Chapter I, all TCs not in S/DR or P/PO account for less than 20% of all TCs. Given the requirement for a 36-h NOGAPS forecast (for calculation of backward predictors), even using a sample inclusion criterion that the storm remain in the same pattern/region combination for only $T = 0$ h, only 55 usable cases are available for a C/MW combination pattern/region of the P /MW and S/MW pattern/regions, 45 usable samples for the S/WR combination, and 17 samples for the G/MW combination. The Multiple TC Poleward and Equatorward Flow (M/PF and M/EF) combinations contain only 24 and 30 usable cases, respectively. No usable G/MW cases are in this sample. Obviously, if the inclusion criterion is increased, even these small sample sizes would decrease substantially. These inadequate sample sizes are consistent with the small percentage of TCs that occur in these pattern/region combinations, as discussed in Chapter I. Given these small samples, no specific regression equations may be developed for TCs in these other pattern regions.

A number of factors were expected to make application of multiple linear regression techniques difficult with some TCs. The Systematic Approach discussion in Chapter I noted the complex nature of TC tracks in pattern/region combinations other than S/DR and P/PO. The complex nature of some of these TC tracks make these storms more susceptible to lower predictability and larger NOGAPS track prediction errors. A number of frequently recurring forecast scenarios in which TCs undergo transition from one pattern/region to another have been identified (CE94, Carr *et al.* 1995), as well as scenarios in which Tropical Cyclone Interaction (TCI) occurs between two TCs.

It should be noted early in this discussion that the material presented in this section provides only a brief overview of the conceptual models for these complex forecast scenarios. Detailed discussions of the environmental and synoptic nature of these storms and the potential error contributions caused by their environment structure are presented in CE94, Carr *et al.* (1995), Webb (1996), and CEB98. As noted in

CE94 and in Chapter I above, part of the central thesis of the Systematic Approach is that the forecaster may improve on dynamical and objective track prediction guidance if he/she is equipped with an implementing methodology or strategy for applying meteorological knowledge bases and conceptual models by taking account of expected guidance errors. Development of this implementing strategy is the ultimate goal of the Systematic Approach. One strategy and methodology under development is the Systematic Approach Expert System (Carr 1997, personal communication).

Given the results in Figs. 18 and 20 that the regression equations developed from the combination of all synoptic pattern/regions provided comparable adjusted NOGAPS track forecasting improvements for the S/DR and P/PO subsets, it is of interest to determine if this PR/ALL regression set would also result in improvements in all remaining pattern/regions. Because the all remaining subset includes many of the unusual, complex, and difficult tracks discussed above, the unadjusted NOGAPS errors (boxes in Fig. 22) are larger than in S/DR (Fig. 18) or in P/PO (Fig. 20). By definition, the all remaining cases must have larger errors than the mean unadjusted NOGAPS errors in Fig. 17 after the removal of the smaller errors associated with the S/DR and P/PO subsets. Notice that these unadjusted NOGAPS errors approach 400 n mi at 72 h.

It is important that the same PR/ALL regression set (as in Fig. 17) also results in a reduced adjusted NOGAPS track error for all remaining pattern/region combinations (Fig. 22). The percentage improvement ranges from 61% at 12 h, 21% at 36 h, to 10% at 72 h. This suggests that the post-processing of a single set of 10 regression equations involving forward and backward NOGAPS predictors only to 36 h has applicability in all pattern/region combinations. At least based on tests with the development samples

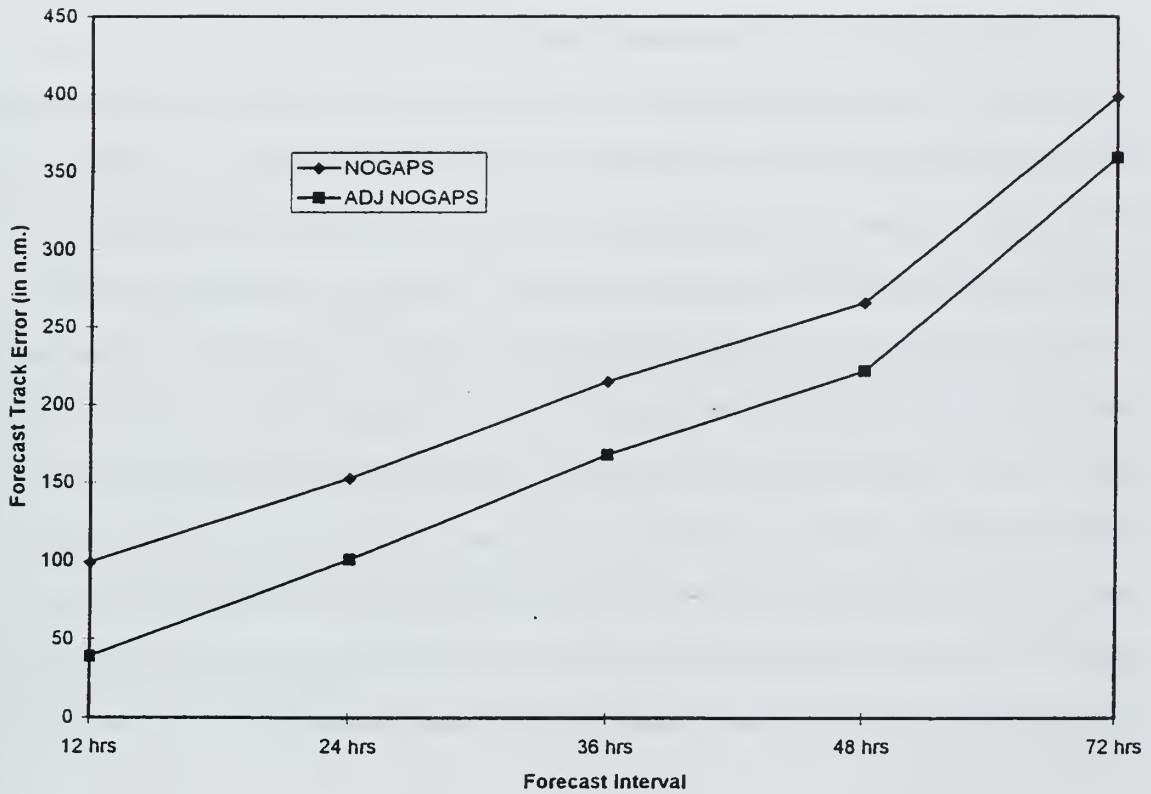Figure 22. NOGAPS track forecast errors as in Fig. 17, except for all TCs not in S/DR or P/PO pattern/region combinations at the initial time. The unadjusted (diamonds) NOGAPS errors for this subsample are compared with the adjusted NOGAPS errors from a regression equation developed for all TCs (boxes), as in Fig.17. A separate set of regression equations was not derived for this subsample of cases.

only, the second goal related to operational utility mentioned at the beginning of this chapter can be achieved with only a single set of 10 regression equations that is useful for all pattern/region combinations.

E.   VALIDATION WITH AN INDEPENDENT DATA SET

A valid criticism of the regression tests in previous sections is that they are all performed on subsets of the development set. As discussed in Chapter III.A, use of the "3/3" development set eliminated the possibility of withholding an independent test set that could be used for validation of the forecast track improvements. Because the PR/ALL regression set has been demonstrated to apply to the S/DR (Fig. 18), P/PO (Fig. 20), and all remaining pattern/regions (Fig. 23), it is not necessary to know the initial pattern/region to apply this NOGAPS adjustment technique. Consequently, an independent data set is available for testing from the NOGAPS forecasts during the just-completed 1997 season. Since the data set does not have to be stratified into pattern/region combinations, the complete NOGAPS forecast set could be used as a test set with the PR/ALL equation set. Notice that the unadjusted NOGAPS mean 72-h track forecast errors during 1997 are less than 300 n mi. By comparison, the unadjusted NOGAPS 72-h errors were about 350 n mi during the 1992-1996 period used to develop the PR/ALL equation set. As noted in Chapter I, a number of improvements have been made to the NOGAPS model during this period, notably in the representation of TC structure using synthetic observations and an increase in horizontal resolution by a factor of two in June 1994.

It is noteworthy that NOGAPS track forecast improvements throughout the forecast interval are obtained from the 1992-1996 PR/ALL regression equation set applied to a model that has been improved. Improvements relative to the unadjusted NOGAPS forecast errors range from 50% at 12 h, 12% at 36 h, and 6% at 72 h. Thus, the equations developed using 1992-1996 data may still result in adjusted NOGAPS track forecasts that are improved. Although it would clearly be desirable to re-calculate the regression

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equations at the end of each typhoon season to take advantage of a larger sample size, the forecast

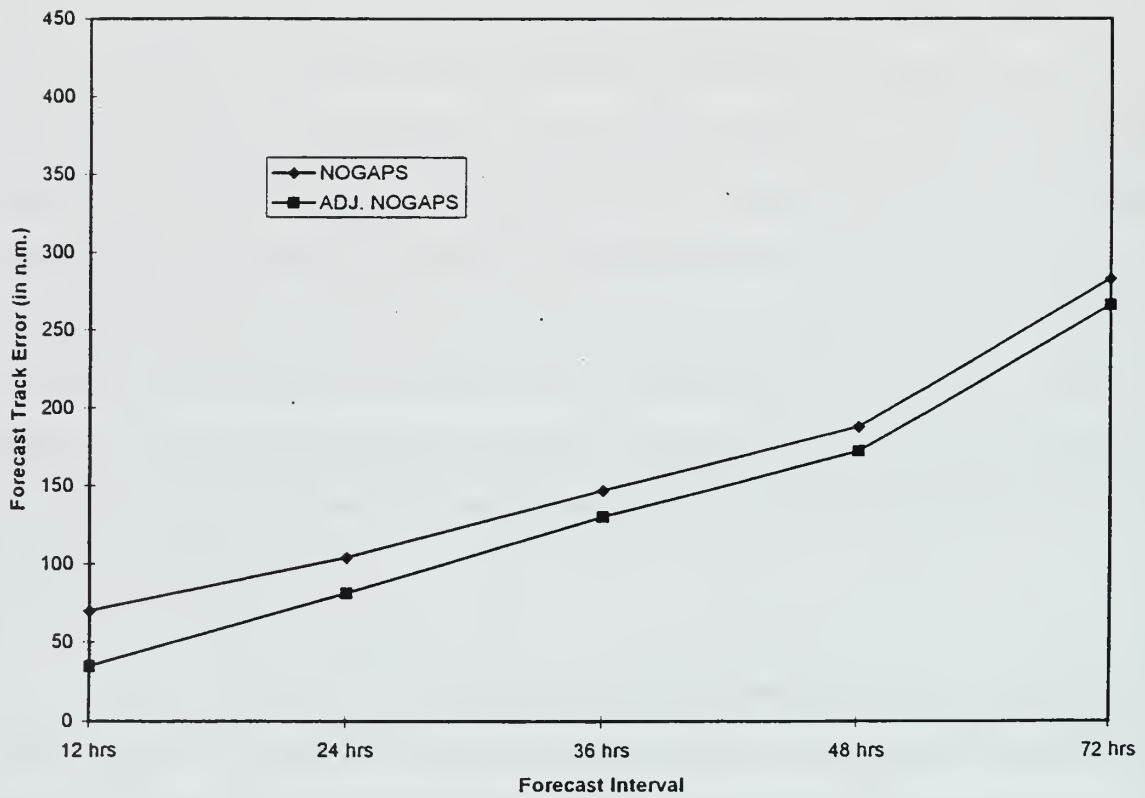improvement achieved in the independent 1997 sample suggests this is not absolutely necessary.

Figure 23. Application of the PR/ALL regression equations as in Fig. 17, except for an independent set of 1997 NOGAPS TC track forecasts.

IV.   CONCLUSION

A.   SUMMARY

Statistical regression techniques have been developed to adjust (or post-process) NOGAPS TC track forecasts to reduce systematic errors and decrease the standard deviation of the errors. Regression equations have been first developed and tested on the entire data base during 1992-1996 as a control set prior to separate application to individual synoptic pattern/region combinations. This set of PR/ALL equations is compared to a new set in which an extrapolated initial NOGAPS position replaced the CARQ 00-h position in the first set. The quality of the regressions was unchanged from using quadratic extrapolation techniques to derive a NOGAPS 00-h position rather than the CARQ position. A second modification has been made to the PR/ALL equation set by developing and testing regression equations that required only 00-36 h forward predictors rather than also requiring the 48- and 72-h NOGAPS positions. Since this modification produces track forecasting improvements comparable to those obtained using 00-72 h forward predictors, the requirement for the 48- and 72-h predictors is dropped. Requiring only 00-36 h forward predictors allows the use of a larger development data set, and enhances the operational utility of this technique by allowing it to be applied when only short term (36-h) NOGAPS forecasts are available. The 36-h PR/ALL regression equations are used for the remaining tests below.

The main hypothesis of this thesis that NOGAPS statistical adjustments will be more effective if used only for TCs in the same pattern/region is tested by the development of separate regression equations for TCs in the S/DR and in the P/PO pattern/region combinations. Adjusted NOGAPS TC track forecasts with the pattern/region-specific regression sets did not have significantly smaller errors than those adjusted NOGAPS forecasts based on the PR/ALL equation set. Surprisingly, similar good results are obtained by applying the PR/ALL equation set to all test data sets, regardless of the initial pattern/region. That is, significant error reductions throughout the forecast period are found in the remaining pattern/region

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combinations other than the S/DR and P/PO combinations. Because the PR/ALL regression equations could be applied to all pattern/region combinations of the development set, NOGAPS forecasts during the recently completed 1997 typhoon season could be tested as an independent set, without waiting for the synoptic pattern/region classification to be done. Even though the 1997 NOGAPS forecast errors are smaller than in the development 1992-1996 sample, the application of the same PR/ALL regression equations results in further improvement in the NOGAPS mean errors. Thus, the track forecast improvements derived on this data set may prove to be operationally significant.

B.   CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

The ultimate goal of this study is to develop regression adjustments to NOGAPS tracks that may be applied operationally by forecasters at JTWC. The surprising result is that classifying a TC in a pattern/region combination is not necessary to apply this regression technique to modify the NOGAPS forecast track such that the track error would be reduced. Coupled with other dynamical and objective forecasting aids available to JTWC forecasters, these techniques have the potential for significant error reduction in TC track forecasts.

It is noteworthy, and operationally significant, that these regression techniques generate significant track forecasting improvements for TCs in the S/DR and P/PO pattern/regions, since these TCs account for more than 73% of all storms which occur. It is also significant that the technique produces track forecasting improvements in the remaining pattern/regions as well. It is possible that larger sample sizes in the future will justify regression sets within the separate pattern/regions. In addition, a number of potential ways to examine NOGAPS track errors may be considered for future work.

In this study, NOGAPS errors are calculated in the x and y coordinate system. Both the CLIPER and JTWC errors have been shown by W96 to be larger in one coordinate (usually along-track or AT) than

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in the other (cross-track or CT), depending on the pattern/region combination. The statistical adjustments performed in this study might be done in AT/CT coordinates, as well. To some extent, the x,y corrections are similar to AT,CT corrections for the westward-moving storms in S/DR and CT,AT corrections for the poleward-moving storms in P/PO. This revised output may help the forecaster better visualize track modifications. One problem with using the AT/CT coordinate system is that the displacements are calculated relative to the actual track segments, which of course would not be known at the time of the forecast. What is known is the CLIPER track, and the AT/CT displacements could be calculated relative to the CLIPER track segments.

As noted in Chapter III, these regression techniques can be used most effectively if a method is developed to isolate those cases and scenarios in which the techniques are expected to fail or be degraded. The "method" for isolating these scenarios will be the Systematic Approach Expert System now under development. Ideally, this system will alert the forecaster when special treatment of a NOGAPS forecast is required. The expert system logic and knowledge base should allow the forecaster to isolate a track forecasting scenario, and either apply track modifications such as those used in this study or the statistical-synoptic techniques developed by Chen *et al.* (1998), or to apply other empirical adjustments to the forecast track based upon the nature of the expected pattern/region and environmental (background) conditions.

Currently, the expert system takes the form of a "selective consensus" approach, as developed by Carr (1998, personal communication). In complex track forecasting scenarios, there are often significant departures in the tracks of two dynamical models. In the selective consensus approach, conceptual models such as those discussed in Chapter III and in Schnabel (1998) are used to identify likely error sources that would allow an informed decision to reject one. Two "clusters" of dynamical and objective aid tracks could be examined, each representing different track scenarios. Possible decisions might be to: (1) reject one cluster as being erroneous, and form consensus forecasts from the remaining cluster; or (2) allow that the track is at a bifurcation point, and that either cluster is a possible solution depending on small changes in the TC or the environment.

An alternate approach may be to use statistical techniques to detect those NOGAPS forecasts that are likely to have large errors. For example, a statistical approach might involve discriminant analysis, in which the NOGAPS error distribution is grouped into classes, such as above average, average, and below average zonal (and/or meridional) errors. The same set of predictors developed and used for this study might then be supplied to the discriminant analysis to see whether these error categories can be resolved. Even if the discriminant analysis was not able to separate unambiguously all of the independent cases into each of the error types, an examination of the predictors selected for the discriminant function at different times and for different error types may provide a basis for detecting certain scenarios that lead to NOGAPS error types (e.g., too far west in S/DR). This knowledge can be incorporated into the selective consensus approach.

Another alternative may involve the use of conditional logic to categorize likely errors and characteristics of NOGAPS (or other objective aids). For example, given one characteristic of a NOGAPS forecast, in combination with a second condition from another dynamical model, then (accept, reject, modify) the NOGAPS forecast. This is the general approach of the selective consensus system, in that a series of conditions are subjectively isolated from case studies, and applied by the forecaster in an expert system. This technique might enhanced if these conditions can be statistically derived from the data base used in this study. The Classification And Regression Trees (CART) software by Breiman *et al.* (1984) may provide an effective tool for exploring this application. This software algorithm constructs a decision tree to classify according to a given category, such as the magnitude of the NOGAPS error, or whether to accept, reject, or modify the NOGAPS track.

The NOGAPS forecast data base used in this study will provide many opportunities for assisting the forecaster in determining whether and how to use dynamical and objective forecast guidance. Whatever techniques are applied, whether subjective deductions based on case studies and conceptual models or statistical approaches such as the one developed in this study, the focus needs to be on what

information the forecaster has available at the initial time to determine the reliability of NOGAPS or other forecast guidance. One advantage of statistical approaches such as the one presented here is that a confidence measure is also generated. That is, some measure of the likely success of the technique is produced (such as an 80% likelihood that a case is in a given category). This information can be applied in the Systematic Approach Expert System, in which a decision has to be reached on which dynamical and/or objective guidance shall be considered and what weight should be given to that guidance.

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