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Tropical Cyclone Forecasters Reference Guide
5. Numerical Track Forecast Guidance

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One of the keys to safe and successful naval operations in the tropics is a thorough understanding of tropical meteorology. The Tropical Cyclone Forecasters Reference Guide is designed primarily as a ready reference for midlatitude forecasters required to provide tropical meteorology support to staff commanders. This report provides a comprehensive overview of numerical forecast guidance used to assess tropical cyclone motion and is Chapter 5 of the reference guide. Subjects discussed include global and regional numerical modeling, major warning center operations, tropical cyclone numerical forecast aids, numerical modeling terminology, and applications of numerical forecast guidance to tropical cyclone forecasting.

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TROPICAL CYCLONE FORECASTERS REFERENCE GUIDE
5. NUMERICAL TRACK FORECAST GUIDANCE

The Joint Typhoon Warning Center (JTWC) and the National Hurricane Center (NHC) use a variety of Numerical Weather Prediction (NWP) products and objective techniques for guidance in the tropical cyclone warning process. Multiple techniques are required, because each technique has particular strengths and weaknesses which vary by basin, numerical model initialization, time of year, synoptic situation and forecast period (JTWC ATCR, 1991). Forecasters at sea use global and regional model output on a daily basis and may see reference to objective guidance in tropical cyclone warnings and prognostic discussions. This chapter provides a brief overview of modeling terminology and objective guidance. Background information on numerical modeling and definitions are given in Appendix A, current global numerical model characteristics are given in Appendix B, and expanded discussions of operational objective aids are given in Appendix C.

1. GLOBAL AND REGIONAL NUMERICAL MODELS

Most major forecast agencies (e.g., the National Weather Service, U.S. Navy, etc.) operate central weather facilities where operational global and regional atmospheric models are run at least daily. These models provide up to five- or ten-day forecasts of parameters such as geopotential heights, temperature and relative vorticity. Tropical cyclone forecasters routinely use the graphical output from these models (e.g., the constant pressure charts) to assist in determining how environmental processes such as large-scale steering flows and vertical wind shear affect tropical cyclones.

The following are descriptions of a few of the numerical models in use around the world for forecasting tropical cyclone motion. Specific aspects of the models change as the models continue to be development. The following are descriptions of model status during the later half of 1993.

1.1 U.S. Navy

The U. S. Navy primarily uses two operational models for NWP: NOGAPS and NORAPS.

1.1.1 NOGAPS

The Navy Operational Global Atmospheric Prediction System (NOGAPS) is a medium-*resolution*[1] global *spectral model (T79)* with 18 vertical levels. This provides a nominal horizontal resolution of approximately 125 km at the equator.

NOGAPS uses a modified version of the Arakawa-Schubert (1974) cumulus parameterization scheme to model the effects of subgrid scale cumulus convection.

In addition, in 1990, *synthetic tropical cyclone observations* were introduced into NOGAPS in an effort to better depict the

[1] Definitions for *italicized* terms are given in Appendix A.

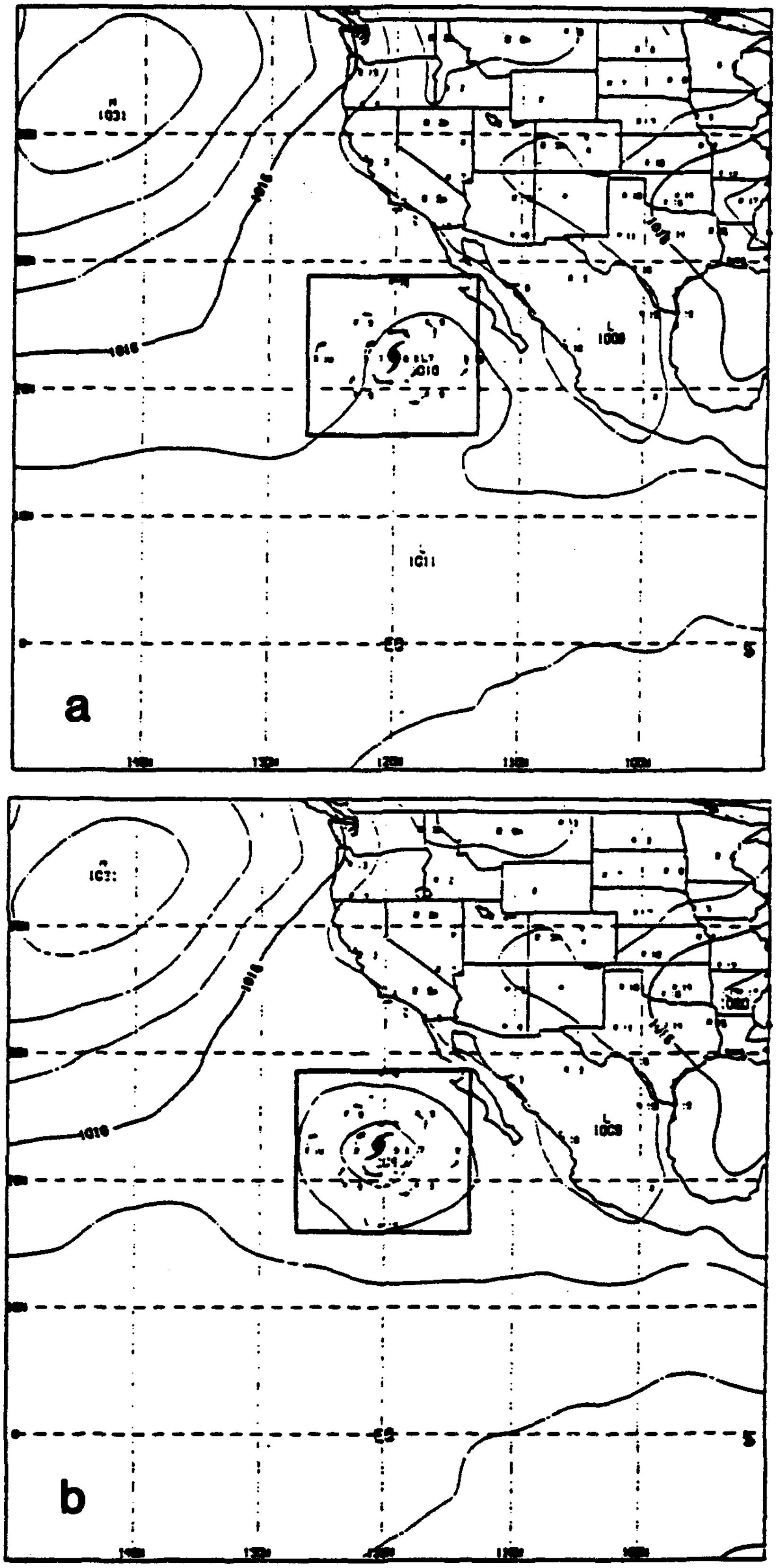

Fig. 5.1. (a) *Multivariate optimum interpolation* (MVOI) sea level pressure analysis (without synthetic wind observations) for Hurricane Genevieve at 22N, 120W, 1200 UTC 16 July 1990. (b) Same as in (a) except analysis included synthetic observations. (Clune, et al., 1991).

effects on the atmosphere of tropical cyclones (Fig. 5.1).

1.1.2 NORAPS

The Navy Operational Regional Atmospheric Prediction System (NORAPS) is a high-resolution regional model. NORAPS is a *finite-difference* model which incorporates high resolution *boundary layer* physics for predicting complex circulation patterns (particularly those associated with complex terrain) with greater detail. The horizontal resolution is currently 40 km with 21 vertical levels. Seven of these vertical levels are below 850 mb.

NORAPS currently runs in a limited number of selected regions. Future plans call for NORAPS to run in any region of the world upon request and for the horizontal resolution to increase to between 10 and 40 km. This increase in resolution will require significant improvements in *boundary conditions* and terrain features as well as a significant increase in run time.

1.2 European Center for Medium Range Weather Forecasts

The European Center for Medium Range Weather Forecasts (ECMWF) numerical model is a high resolution spectral model. This model represents a cooperative effort among several European countries to provide global numerical weather predictions for its members.

The current model is a T213 with 31 vertical levels. Therefore it has a horizontal resolution of approximately 50 km at the equator, which is significantly higher than other operational global numerical weather prediction systems.

1.3 National Meteorological Center

The National Meteorological Center (NMC) numerical model is a high-resolution spectral model. NMC is the civilian counterpart to FNOC. The output from the NMC model is disseminated to users via digital facsimile (DIFAX) directly from NMC, via the Navy/NOAA Oceanographic Data Distribution System (NODDS), and through various commercial companies.

The current horizontal model resolution is a T126, or approximately 80 km with 18 vertical levels.

1.4 Japan Meteorological Agency

The Japan Meteorological Agency (JMA) is the designated regional tropical cyclone forecast agency for the World Meteorological Organization (WMO), whose area of responsibility is the western North Pacific in the vicinity of Japan. JMA supports their active role in tropical cyclone predictions by using a medium-resolution spectral model, the Global Spectral Model (GSM), and the Typhoon Model (which is discussed in Appendix C) to develop track forecast guidance. The two regional models, the Asia Spectral Model and Japan Spectral Model are used as product quality control.

JMA is the Japanese civilian counterpart to FNOC in the western North Pacific. The output from GSM is disseminated to users via weather facsimile broadcast from and through commercial companies.

The horizontal resolution of the GSM is T106, or approximately 95 km with 21 vertical levels.

2. GENERAL CATEGORIES OF OBJECTIVE AIDS

Many objective aid forecasts are generated using initial conditions or forecasts supplied by a global or regional numerical model. Objective aids run at FNOC use NOGAPS global fields while those run for the National Hurricane Center use the NMC global and regional fields.

The U.S. Navy tropical cyclone warning agencies (JTWC and the Alternate JTWC at Pearl Harbor) define six different types of objective aids, while the National Hurricane Center (NHC) defines five categories (Table 5.1). The format used at JTWC are discussed in this section. For a detailed discussion of individual objective aids, see Appendix C.

Table 5.1 Tropical Cyclone Forecast Aid Categories.

NHC	JTWC
Climatological	Extrapolation
Statistical	Climatology and Analogs
Statistical Synoptic	Statistical
Statistical Dynamical	Dynamic
Barotropic Dynamical	Hybrid
	Empirical

2.1 Extrapolation

Past speed, direction and intensity trends are used as the initial guidance for short term forecast decisions, especially during the first 12 to 24 hours. This aid is the best short term guidance available. Only the current tropical cyclone track is used as input for this model.

2.2 Climatology and Analogs

Climatology and analog aids are techniques that use historical storm records as a method of exploiting current and past motion and intensity trends to project future storm positions and intensities. Current and historical tropical cyclone tracks are used as input for these models. Numerical model output is not required input for these models.

2.2.1 Climatology

These techniques directly use the past motion of the current storm, and average motions of selected historical storms without application of any regression analysis to minimize the average forecast error for some dependent data set. Time and location windows relative to the current position of the storm determine which historical storms are used to compute the forecast guidance.

2.2.2 Analogs

JTWC's and NHC's analogs use the same data base as the climatology aids except the analog techniques impose additional restrictions (e.g., tropical cyclone speed and direction of motion) to select which storms are used to compute the forecast positions.

2.3 Statistical

The common feature of these models is that regression analysis is used to minimize forecast error. Usually the 24, 48 and 72 hour forecast positions are determined using *regression* equations for the various types of measured quantities. These predictors may be any combination of parameters from the present storm, historical storms (climatology), synoptic analyses, and numerical prognoses.

Many of these techniques require global numerical model analyses and forecasts.

2.4 **Dynamic**

Dynamic forecasts are based on numerical integration of mathematical equations that approximate the physical behavior of the atmosphere. Dynamic forecasts are derived in two different ways. Some actually track the movement of a tropical cyclone vortex, which is either explicitly resolved by or bogussed into a global or regional model. Regional fine mesh models use various horizontal and vertical resolutions to compute storm motions. In addition, they can apply *barotropic or baroclinic* equations to create the forecast tracks resulting in a variety of solutions. The simplest approach in numerical forecasting is to use either global or numerical model wind fields to compute a steering flow that advects a point vortex. These techniques can also provide useful forecast information, particularly speed forecasts.

2.5 **Hybrid Forecast Aids**

These objective aids combine elements of two or more of the above categories. The elements are blended, based on performance weighting characteristics. For example, if the five best performing forecast aids are blended, the track predicted by the number one aid would be weighted higher than the track predicted by the number five aid.

2.6 **Empirical or Analytical**

These subjective techniques are applied by the forecaster and the results are significantly influenced by the experience level of the forecaster.

3. FORECAST CONSIDERATIONS FOR OBJECTIVE AIDS CATEGORIES

Many of the objective aids have peculiar strengths and weaknesses which may be exploited by forecasters at the warning centers (e.g., JTWC or NHC). Sometimes tropical cyclone warning discussions will include descriptions of objective aid behavior and forecaster interpretation of threat behavior. For example:

```
WDPN PGTW 170900
A.  Analyis/Fix Discussion
B:  TYPHOON GAY (17W) CONTINUES TO TRACK NORTHWESTWARD UNDER
THE INFLUENCE OF A STRONG MID-LEVEL RIDGE.  CURRENT NOGAPS
PROGS INDICATE THIS RIDGE WILL REMAIN STRONG OVER THE NEXT 72
HOURS AND THE STORM WILL REMAIN EMBEDDED IN THE EASTERLY FLOW
SOUTH OF THE RIDGE THROUGHOUT THE FORECAST PERIOD.  CURRENT
DYNAMIC AND STATISTICAL AIDS ARE IN GOOD AGREEMENT AND SUPPORT
OUR CONTINUED WEST-NORTHWESTWARD FORECAST.
C:  Intensity Forecast Discussion
D:  Wind Radii Forecast Discussion
```

Knowledge of the strengths and weaknesses of the objective aids can enhance a forecaster's ability to interpret the discussion section and them make forecast recommendations to the on-scene commander.

3.1 Extrapolation

The principal advantage of extrapolation is its ability to account for short term trends of motion and intensification. The principal weakness is the limited time frame in which it remains valid. The validity of an extrapolation forecast quickly erodes as the environment around the tropical cyclone changes.

3.2 Climatology and Analogs

The principal advantage of a climatological model is that, with the exception of errors in the present storm position, they are generally insensitive to initialization problems caused by insufficient and/or misrepresentative data. The principal disadvantage of climatology is that it gives only the average behavior of storms under the average conditions. Therefore, climatology can never handle aclimatological situations. The analog approach attempts to minimize this problem by restricting the historical data base to a small subset that hopefully represents synoptic conditions that are fairly close to those influencing the present storm.

Climatological aids perform best if the storm is in an area with a large number of historical storms. Thus climatology and analog aids should not only be more accurate, but also show less variability from forecast to forecast during the active tropical cyclone season. In the off-season, climatological aids are sporadic performers. An example of this is shown in Figure 5.2. Note the sudden change from a straight to recurve forecast.

Another problem occurs when the tropical cyclone approaches the data sparse region over China. When a storm is moving toward land at a latitude where recurvature occasionally occurs, the climatology forecast will likely predict recurvature (Fig. 5.3). One reason for this is that tropical cyclones usually dissipate over land; therefore, there are fewer straight moving tracks in the climatology data. This is especially true for 72 hour forecasts.

A similar bias exists for storms that are at or near recurvature and potentially within 48 hours of dissipation or extratropical transition. The 72 hour position given by climatology aids will likely contain a significant slow-speed bias, since only a slow moving historical storm would exist long enough to generate a 72 hour best track position.

3.3 Statistical

The principal advantage of statistical regression methods is that they attempt to correct for known and unknown systematic biases caused by data distribution. The principal disadvantage is that statistical regression methods produce forecasts that conform to the average behavior of storms in the dependent data set used in the regression analysis. Again, aclimatological situations are generally not handled accurately. The statistical-synoptic and statistical-dynamic models are also subject to the negative influences of erroneous or missing data that affect dynamic models.

Statistical regression aids can be expected to perform reasonably well when the synoptic situation, as manifested by recent storm motion, does not depart significantly from the climatology. Thus, a statistical regression aid forecast should be viewed with suspicion in the following situations:

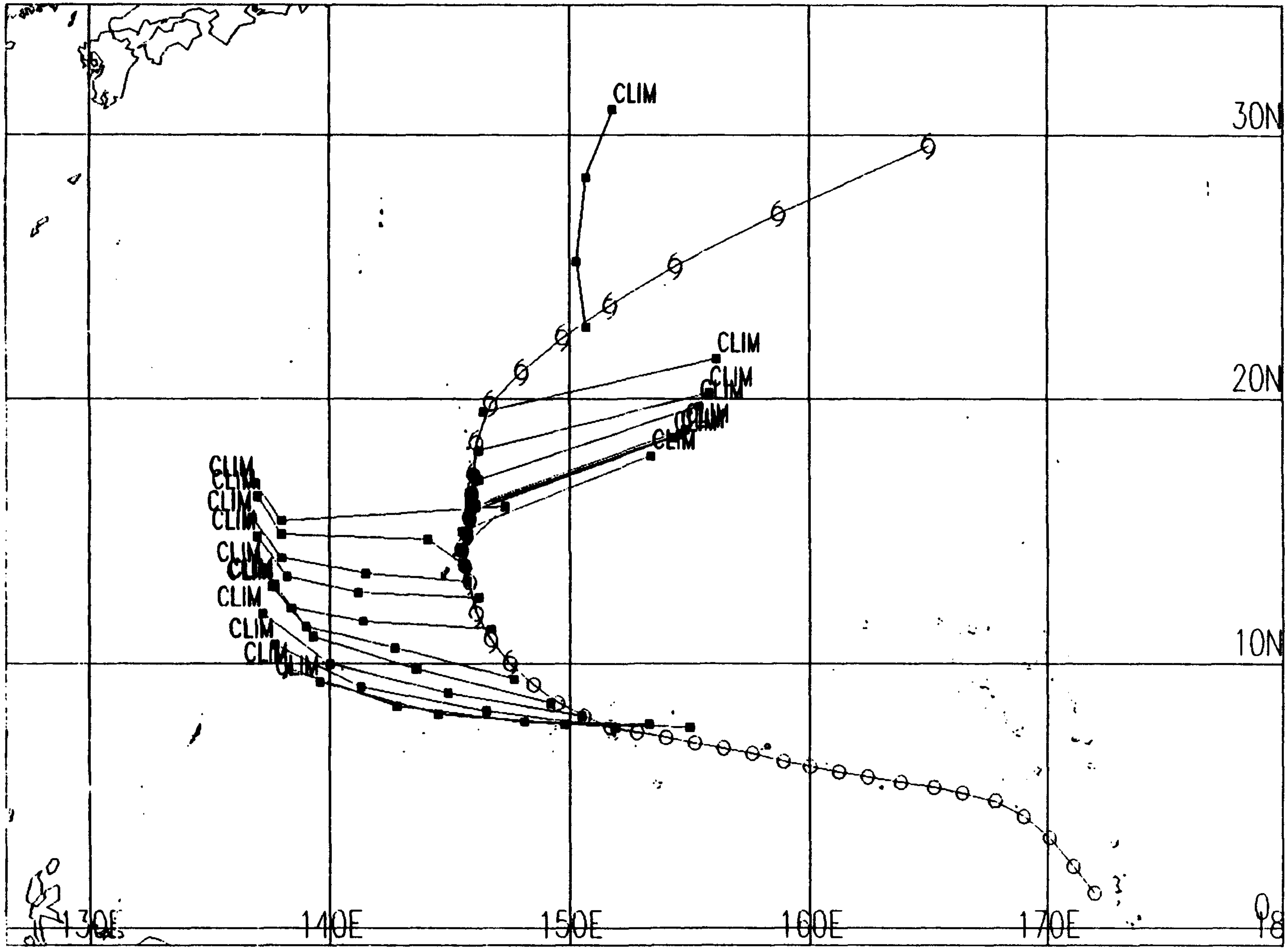

Fig. 5.2. An example of how the climatology objective aid (CLIM) forecast can be sporadic during the off-season in the western North Pacific, for Koryn (01W, Jan 8-19, 1990).

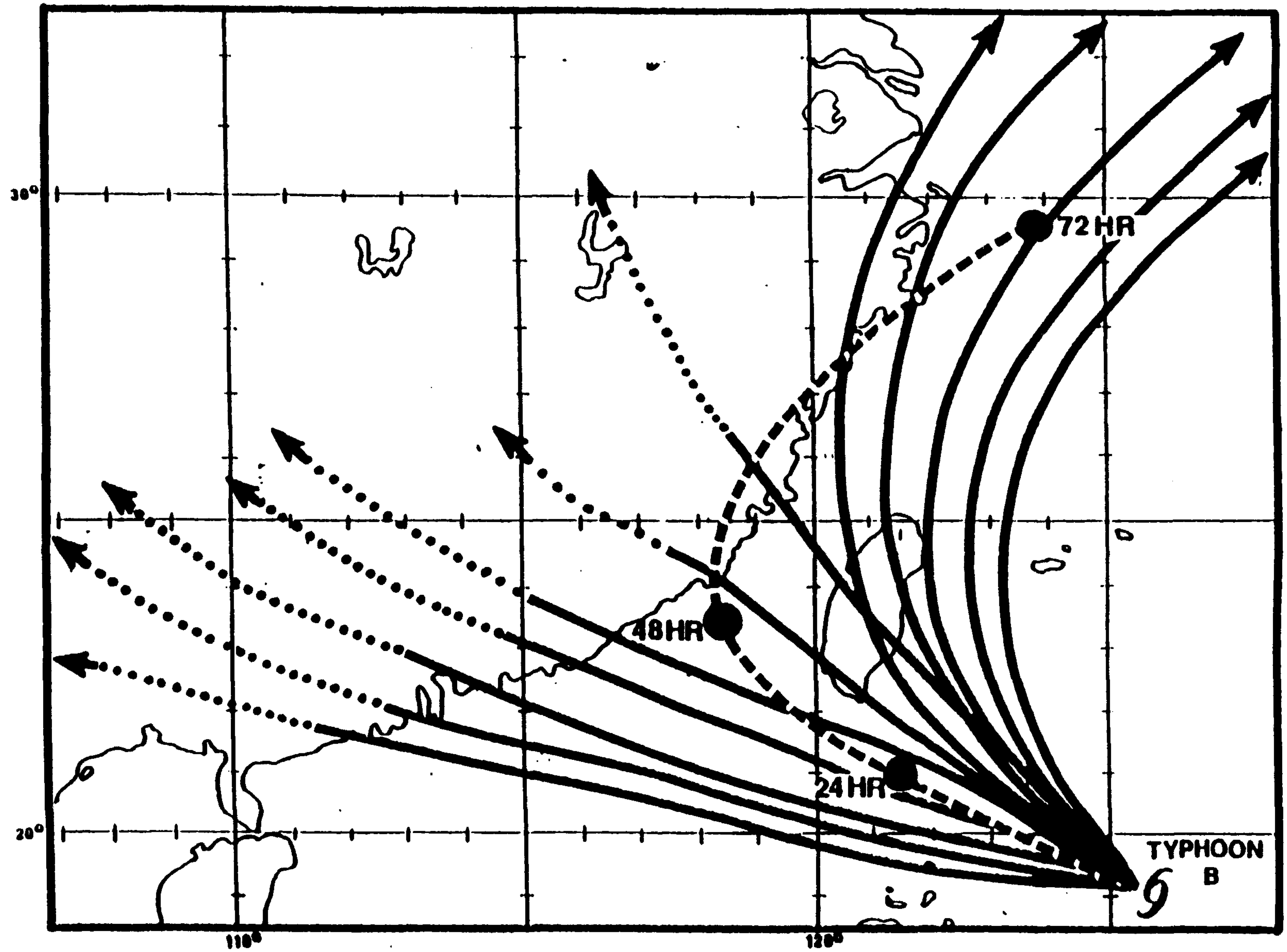

Fig. 5.3. Schematic illustration of recurvature bias in analog/climatology-based forecasts for tropical cyclones approaching land. (JTWC working papers)

(1) Statistical aid forecast is poleward and eastward motion at low latitudes;
(2) Statistical aid forecast is equatorward and eastward motion north of the subtropical ridge;
(3) Statistical aid forecast is stalled or looping motion near ridge axis;
(4) Principal synoptic features significantly displaced from the normal climatological position;
(5) Any storm position that falls outside the tropical cyclone season for the basin.

Statistical regression aids tend to display unusual motion characteristics when they move into data-sparse regions, or have bad past motion inputs or erroneous intensity inputs. Figures 5.4 and 5.5 indicate how WPCLIPER (a statistical regression aid) responds to changes in time of year, latitude, longitude, past position, and initial intensity. WPCLIPER's response to time of year provides a good indication of where WPCLIPER expects the subtropical ridge axis to be.

Other statistical regression aids performance is affected more by the synoptic patterns governing the current motion. For example, CSUM (Colorado State University Model) performs well during periods when the storm is in one of three synoptic patterns, but does not predict the transitions between the patterns. For a storm that starts out equatorward of the subtropical ridge, CSUM tends to keep it moving west-northwest, but suddenly jumps to a poleward track whenever the past motion vector is between 330 and 030 degrees (Fig 5.6). A similar jump takes place when a recurving storm's direction of motion first falls between 031 and 120 degrees.

3.4. Dynamic

The principal advantage of numerical methods is that they are sensitive to the current and future synoptic structure of the atmosphere, as represented by the model, and thus can better handle aclimatological situations. The principal disadvantage of dynamical methods is their sensitivity to insufficient or erroneous data (typically inducing a misplaced vortex), which results in forecasts that, even in the short term, are initialized with the wrong direction/speed (Fig. 5.7). The more sophisticated a numerical model is, the more sensitive it is to inaccurate initialization due to data limitations. The more sophisticated the model, the more rapidly its forecasts can depart from reality due to the growth of data-induced initialization errors. As a result of this weakness, numerical models often require initial tropical cyclone data (e.g., position, intensity and movement) to insure the model vortex at least starts out in the right location and moves in the right direction.

Each numerical/dynamic aid used at JTWC/NHC has its own unique characteristics (strengths/weaknesses). Numerical forecast aids can be based on tracking the movement of the tropical cyclone vortex as represented in a global or regional numerical model, or the aids can be based on steering derived from such numerical models. Thus, the accuracy of the global model used to initialize the dynamic aids is a governing factor of the accuracy of the aid predictions.

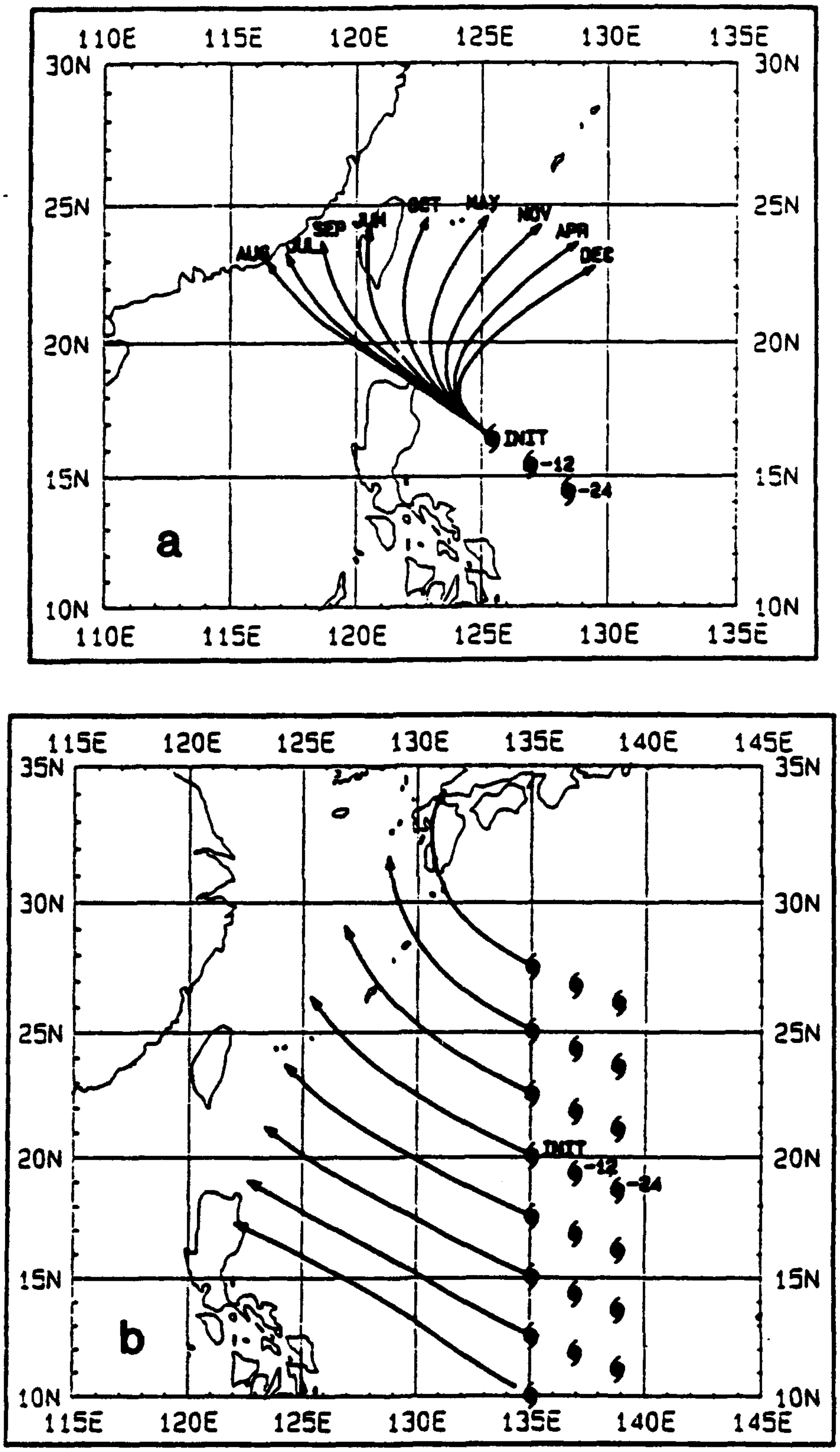

Fig. 5.4. Sensitivity of WPCLPR model to (a) time of year and (b) initial latitude. Shown are 72-h forecast tracks with different initial conditions. (Englebretson, 1992)

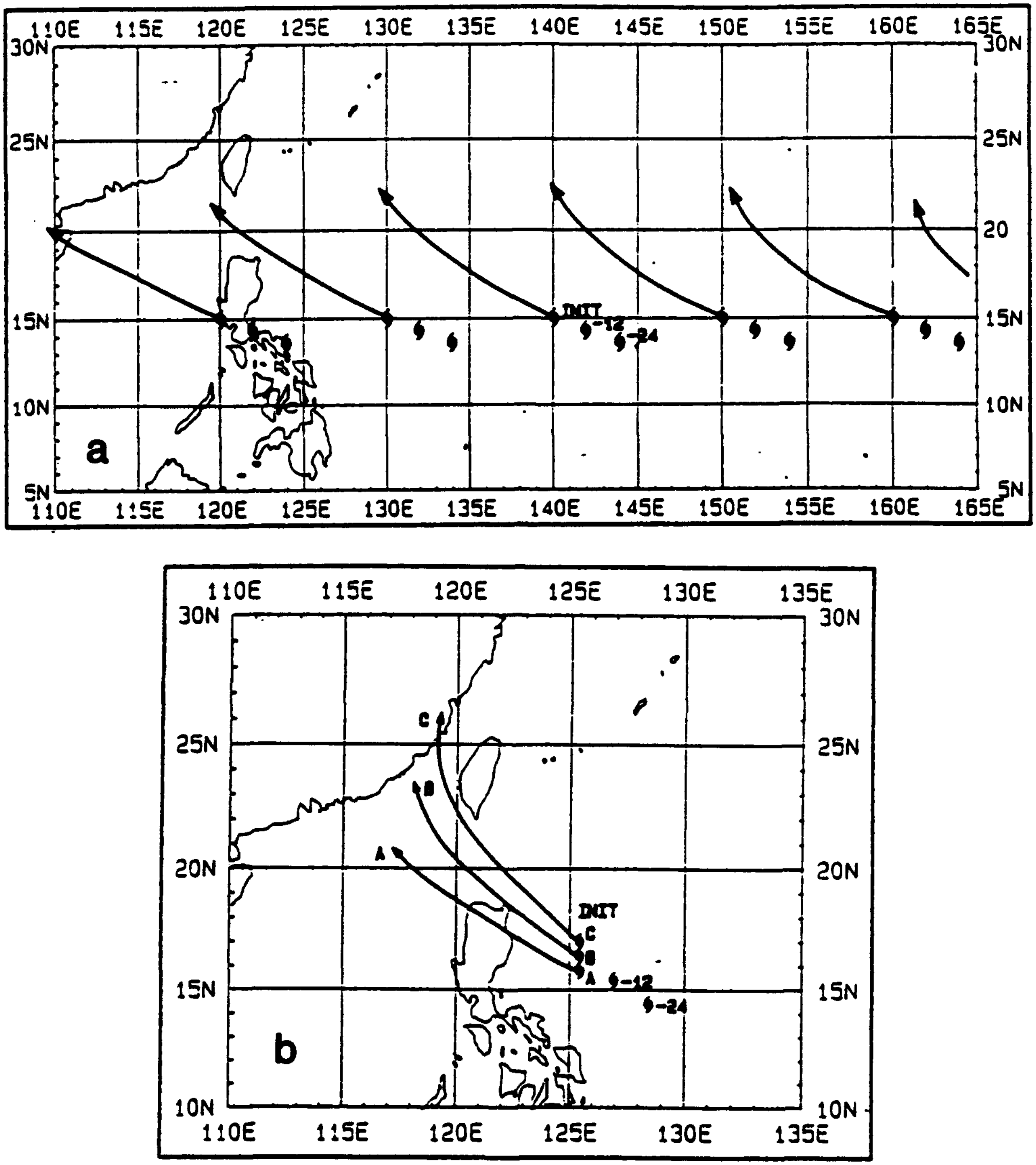

Fig. 5.5. Sensitivity of WPCLPR model to (a) initial longitude and (b) changes in past motion. (Englebretson, 1992)

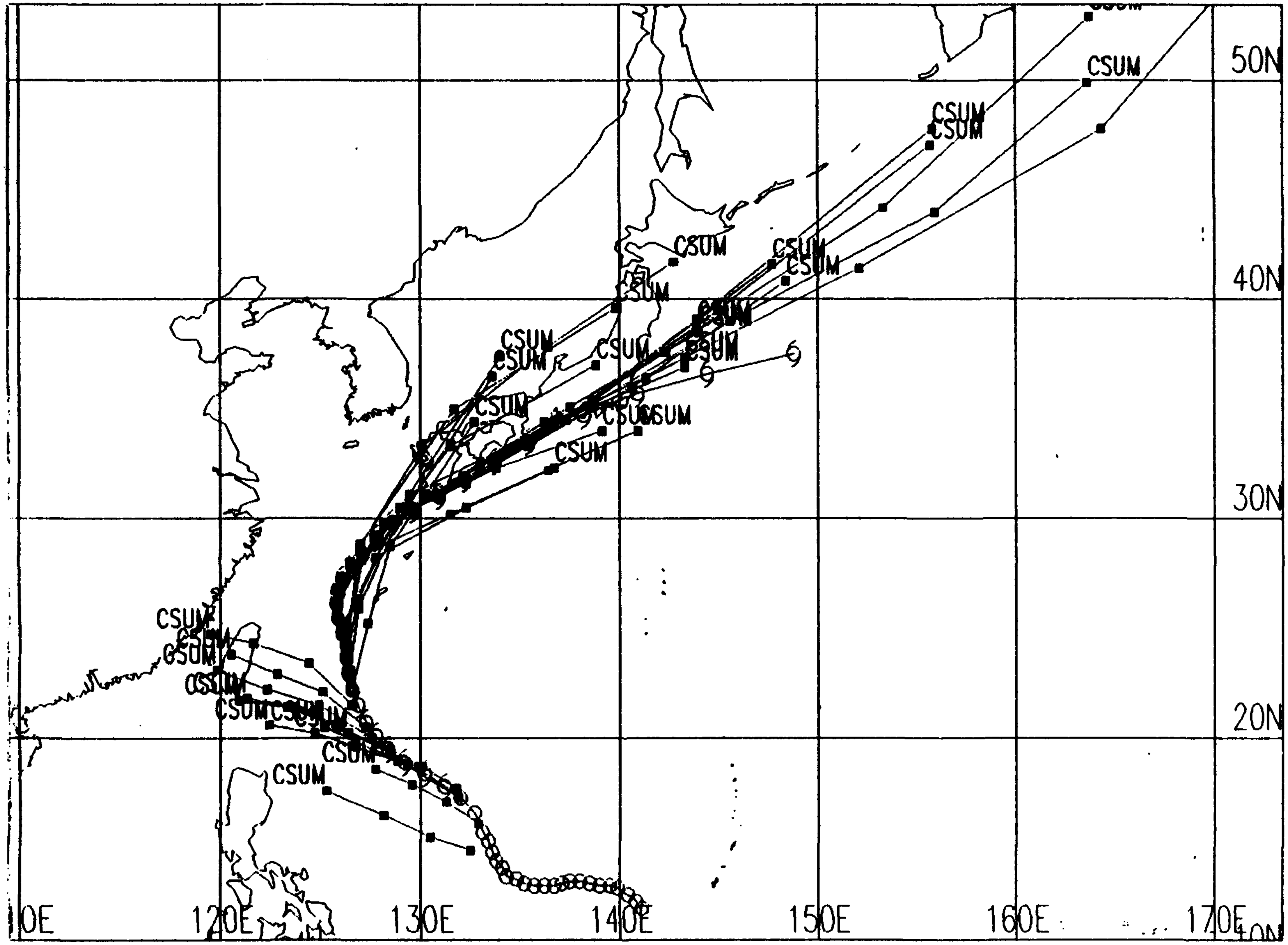

Fig. 5.6. An example of forecasts from the objective aid CSUM. Distinct forecast changes are seen when tropical cyclone direction of motion changes from west moving (less than 330 degrees), to north moving (330 to 030 degrees) to northeast moving (greater than 030 degrees) For Typhoon Gene (21W, 1990). Squares represent the initial, 24, 48, and 72 hour forecast positions. Symbols represent actual tropical cyclone track every six hours.

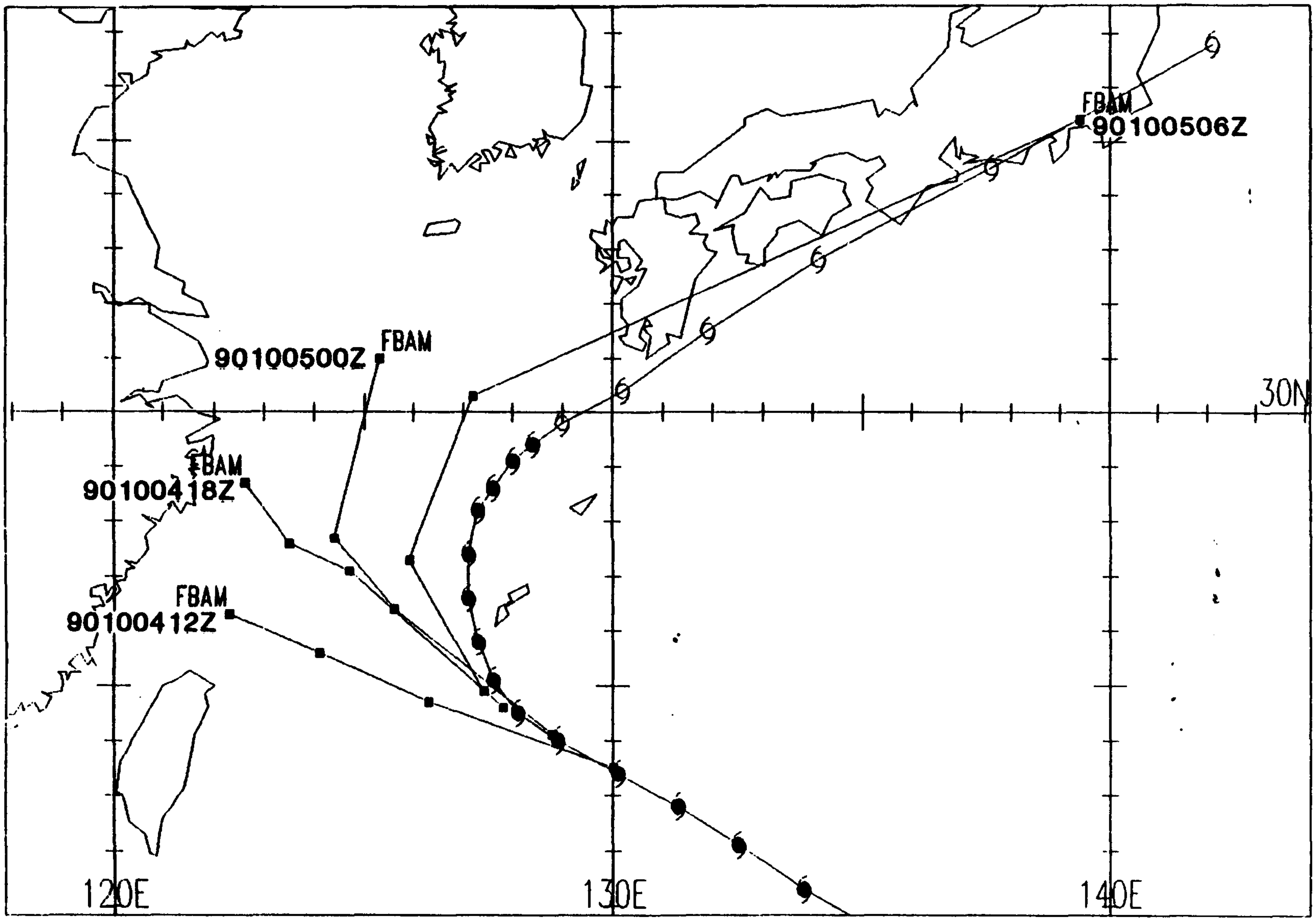

Fig. 5.7. An example of the how the objective aid FBAM tends to "windshield-wiper" the forecast as the storm approaches recurvature. Some of the early forecasts predicted recurvature along the actual typhoon track. However, the forecasts near recurvature switched back and forth between recurvature and northwestward several times. Squares represent the initial, 24, 48, and 72 hour forecast positions for Typhoon Hattie (22W, 1990). Symbols represent actual tropical cyclone track every six hours.

3.5 Hybrid

Hybrid aids attempt to capitalize on the strengths of several types of aids by combining the outputs using statistical methods. The principal disadvantage of this type of forecast aid is that it also capitalizes on statistical regression weaknesses in aclimatological situations.

The primary consideration when using a hybrid aid that attempts to capitalize on climatology can be best described by the following example. To capitalize on the strengths of HPAC (Half Climatology and Persistence) a measure of the extent of deviation from climatology is the angle between XTRP and CLIM. If this angle exceeds 60 degrees, then HPAC should be disregarded unless it has been performing well statistically on the current storm. Figure 5.8 shows an extreme example of degradation in a HPAC forecast caused by the combined effects of a significant slow speed bias in the 72 hour CLIM forecast and the fast 12-hour past motion of RUSS (31W, 1990) which, of course, is retained by XTRP throughout its forecast.

3.6 Empirical

The principal advantage of these techniques is the ability to exploit pattern recognition techniques that the forecaster develops with experience. These pattern recognition techniques can eliminate major errors associated with missed recurvature and acceleration of storms into the mid-latitudes. The major weakness lies in the amount of time required to gain the experience level necessary to accurately apply these techniques. The techniques require the use of tables and nomograms, which must be applied through adaptation of the technique procedures to the current situation through modifications based on the forecasters experience. These aids are best used by seasoned forecasters who can quickly evaluate changing conditions.

4. NUMERICAL GUIDANCE WARNING/FORECAST PROCEDURES

As the previous discussion indicates, application of objective aid guidance to tropical cyclone forecasting is a tricky business. This section describes how the forecast centers apply objective aid guidance to their forecast procedures; and how a single station forecaster, or forecaster at sea, could apply what is written in the official forecast discussions to forecast recommendation preparations.

4.1 JTWC Numerical Procedures

JTWC does a comprehensive analysis of the current and forecast synoptic situation to determine the governing synoptic environment and the long term motion trends. Then the Tyhoon Duty Officer downloads and displays the current set of objective aid forecasts and evaluates the pattern produced by the set of forecasts according to the following principles. First, the degree to which the current situation is considered to be and will continue to be climatological is further refined by comparing the forecasts of the climatology-based objective techniques, dynamically-based techniques, and past motion of the present storm. This assessment partially determines the relative weighting given the different classes of objective techniques. Second, the spread of the pattern

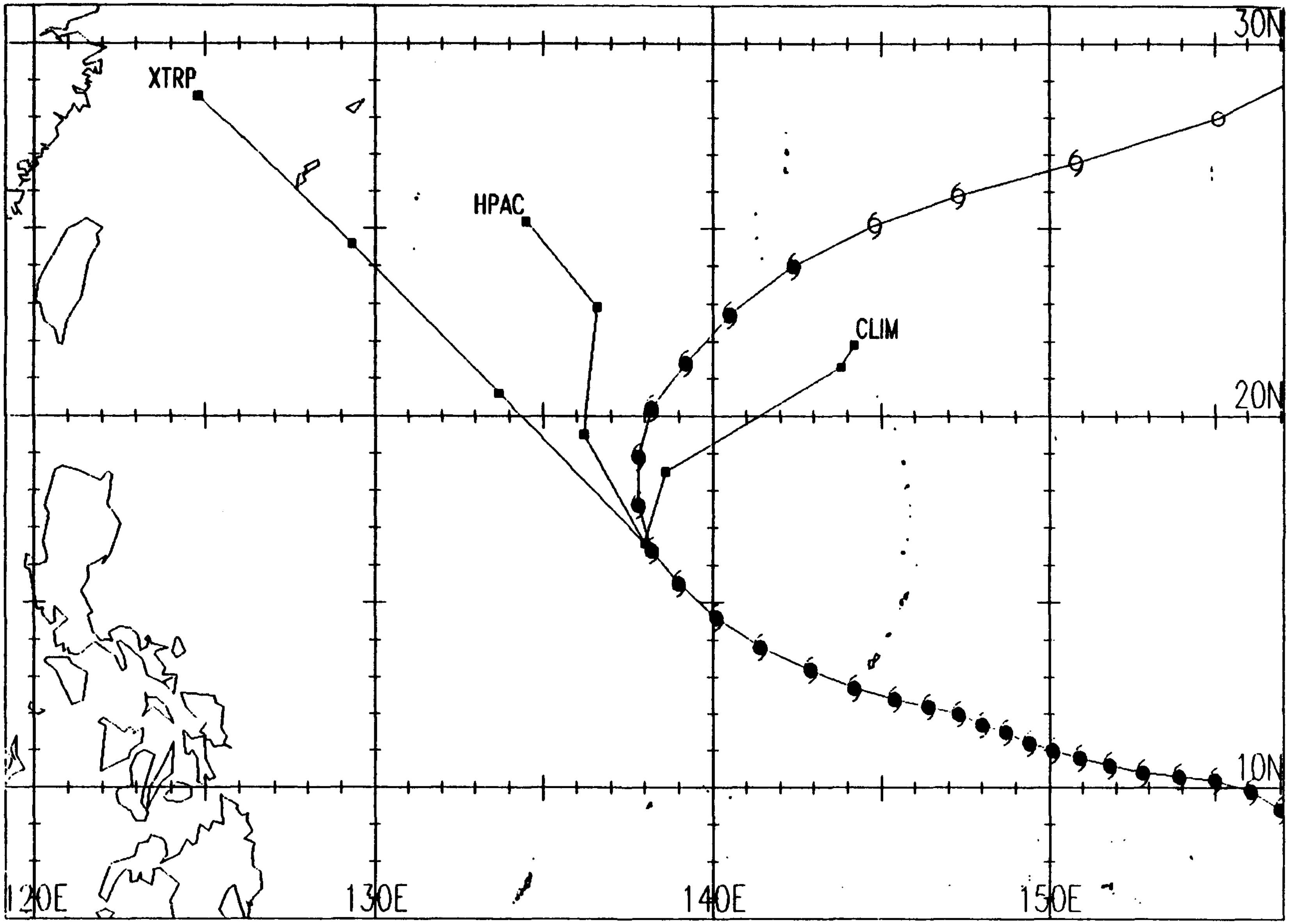

Fig. 5.8. An example of the climatology objective aid (CLIM) slow speed bias for Typhoon Russ (31W, 1990) due to lack of climatological data north of the subtropical ridge. Squares represent initial, 24, 48, and 72 hour forecasts. Typhoon symbols represent actual tropical cyclone track every six hours. Note the impact on the Half-Persistence and Climatology objective aid (HPAC).

determined by the set of objective forecasts is used to provide a measure of the predictability of subsequent motion, and the advisability of including a low or moderate probability alternate scenario in the prognostic reasoning message or warning. The spread of the objective aids is typically small before and large near recurvature or during a quasi-stationary or erratic movement phase.

The TDO constructs the official forecast giving due consideration to 1) the extent which the synoptic situation is and is expected to remain climatological, 2) past statistical performance of the various objective aids on the current storm and 3) known properties of individual objective techniques given the present synoptic situation. The following guidance for weighting the objective aids is applied:

(1) Weight persistence strongly in the first 12 to 24 hours of the forecast period.

(2) Give significant weight to the last JTWC forecast at all times, unless there is significant evidence to warrant a departure. (Also utilize latest forecasts from regional warning centers, if applicable).

(3) Give more weight to the techniques that have been performing well on the current tropical cyclone and/or are expected to perform well in the current and expected synoptic situation.

(4) Stay within the "envelope" determined by the spread of objective aid forecasts unless there is a specific reason for not doing so (all 12 hour objective aid forecasts are at a significant angle relative to the current motion of the tropical cyclone) (JTWC ATCR, 1991).

4.2 NHC Numerical Procedures

Before numerical aid forecasts are applied at NHC, an analysis of the global, regional and area numerical model analysis and prognosis is performed. This allows the forecaster to formulate an expected long-term tropical cyclone track prior to applying the numerical aids. In addition, ECMWF and UKMO model forecasts are also analyzed to provide an additional input on movement and development of the governing synoptic features.

In addition, current animated satellite imagery is analyzed for qualitative assessment of flow patterns changes. Special emphasis is placed upon animated water vapor imagery for regions of moist and dry flow.

The next step involves detailed analyses of the tropical cyclone itself. These analyses involve all available satellite, reconnaissance aircraft, buoy, and radar data, and ship observations to determine present and past motion, wind and pressure field distributions, etc. This information is used as input data for the five to seven numerical forecast models run during each forecast cycle.

Following the above procedures, the NHC forecaster arrives at an independent forecast based primarily on the guidance received from the NMC model outputs.

4.3 Single Station Procedures

Single station tropical cyclone forecasters monitor tropical cyclones that threaten DOD assets and provide forecast recommendations to area and task force commanders. The commanders then set conditions of readiness to safeguard manpower and materials. The following is a suggested procedure to assess the tropical cyclone warning and its effect on naval operations.

4.3.1 Predeployment Step

Numerical forecast guidance accuracy is key to the accuracy of tropical cyclone warnings. Therefore, it is a good idea to become familiar with the numerical forecast guidance used by forecasters within the deployment area.

The quarterly model performance summary from FNOC, the JTWC Annual Tropical Cyclone Reports, and Diagnostic Reports of the National Hurricane Center provide information on model performance. Pertinent information from these reports should be provided to operations officers and commanding officers during the predeployment briefings and prior to any tropical cyclone evasion evolutions.

4.3.2 Global Model Analysis Step

When a tropical cyclone develops or moves into the forecast area, plot the warning and analyze the current synoptic environment to determine key synoptic features affecting the current motion/intensification trend. This analysis should center on how well the model forecasts verify against the analyses. One suggested approach is to overlay the surface and 500 mb 24, 36, 48 and 72 hour forecast charts on the verifying analyses and mark the areas which indicate significant departures from the analyses. Next identify the key features within 30 degrees longitude and latitude of the tropical cyclone which appear to affect the motion and intensity change.

Check both the overall synoptic pattern and individual values of pressure and wind. By performing this step, quick assessment of the global model performance can be made.

4.3.3 Numerical Guidance Verification Step

In this phase, the tropical cyclone forecast numerical guidance discussion is verified for accuracy and significant departures from the previous forecast discussions. As a first step, plot the official motion/intensity forecasts on the verifying prognostic charts from the numerical model (e.g., the NOGAPS 500 mb 48 hour forecast) and note the location with respect to the major synoptic features identified during the previous step. An initial assessment of forecast confidence can now be made. Table 5.2 shows examples of confidence value assignments.

If a low confidence scenario is identified during the numerical aid verification step, the forecaster must make every effort to understand why this discrepancy exists. A review of the synoptic situation could shed some light on the situation. If the forecast center is changing from one primary forecast scenario to another, the numerical guidance should be described in detail in the prognostic discussions.

Table 5.2. Examples of Numerical Forecast Guidance Confidence Values.

Discussion terminology	Synoptic situation	Forecast confidence
All aids in good agreement	Storm south of strong ridge	High
Motion based on climatological aid guidance	Storm south of strong ridge	High
Motion based on climatological aid guidance	Storm nearing break in subtropical ridge	Low
Motion based on climatological aid guidance	Storm nearing land mass, recurvature indicated	Low
Motion based on statistical aid guidance	Storm south of strong ridge	High
Motion based on statistical aid guidance	Storm nearing break in subtropical ridge	Low
Motion based on statistical aid guidance	Storm north of subtropical ridge	Low, (Forecast speed usually slow)
Motion based on dynamic aid guidance	Tropical cyclone well depicted in global model	High
Motion based on dynamic aid guidance	Tropical cyclone poorly depicted in global model forecast	Low

4.3.4 Forecast Recommendations Step

A forecaster on a ship at sea must remember that tropical cyclone position forecast errors can be quite large. For example, the average forecast errors for JTWC in the western North Pacific are approximately 120 nm at 24 hours, 240 nm at 48 hours, and 360 nm at 72 hours; however, individual forecast errors can be greater than 1000 nm. Therefore, it is important that the on-scene forecaster assess the numerical guidance information received, determine a confidence value for the official forecast, and brief this confidence value to on-scene commanders.

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APPENDIX A
Terms and Definitions

The following provides definitions for some of the terminology used in numerical forecast guidance discussions. Unless otherwise specified, the source of these definitions is Numerical Prediction and Dynamic Meteorology (Haltiner and Williams, 1980).

1. **Multivariate Optimum Interpolation (MVOI)** MVOI is a method for producing a dynamically consistent blending of observations and model forecasts for use as initial conditions for forecast models. The MVOI technique combines first guess fields (usually 6 hour or 12 hour model forecasts) with a wide variety of observational data to generate an analysis of the present state of the atmosphere. An important feature of MVOI is that it minimizes the error in the analysis by accounting for errors in both observations and first guess fields (Goerss and Phoebus, 1992).

2. **Finite Difference Methods** These are methods for approximating derivatives in the equations of motion. Continuous derivatives in differential equations are replaced by finite difference approximations at a discrete set of points in space and time. The resulting set of equations, with appropriate restrictions, can then be solved by algebraic methods.

A finite difference model is one which employs finite difference methods. The resolution of a finite difference model is determined by the spacing of the discrete set of points (grid points) used to approximate the derivatives.

3. **Model Resolution** Model resolution is usually defined as the distance between gridpoints in the model and is of primary interest to operational forecasters. In general, increased model resolution allows for definition of smaller scale features. In data rich areas, this increased resolution allows for more accurate depiction of small scale features.

As a general rule, at least 5 grid points (or 4 grid intervals) are needed to define a weather phenomenon. For example, a model with a horizontal resolution of 125 km can resolve only horizontal phenomena of 500 km or greater. Vertical resolution defines the resolution between the earth's surface and the top of the model. In many cases vertical resolution is variable. For example, a model with 21 vertical levels may have 7 levels in the region below the 850 mb level. In this case, processes in the boundary layer will be much better represented than if the levels were evenly spaced in the vertical.

4. **Primitive Equations Models** Models which use the primitive equations to approximate the state of the atmosphere at the gridpoints were originally called primitive equation models. Early primitive equation models used a system of six equations; three prognostic equations (the x and y components of the momentum equation, and the thermodynamic energy equation) and three diagnostic equations (the continuity equation, the hydrostatic

approximation, and the equation of state) (Holton, 1979). Most models in use these days are primitive equation models.

5. **Barotropic Models** Barotropic models are dynamic models formulated with the assumption that the atmospheric structure does not vary with height. Hence, these models are single level models. One advantage of barotropic models is that they are relatively simple. Examples of barotropic models include BAM, FBAM, MBAM, SBAM, and SANBAR.

6. **Baroclinic Models** Baroclinic models are dynamic models formulated with the assumption that the wind can change with height. As a result, these models must account for multiple levels. One advantage of baroclinic models is that they better represent the instantaneous structure of the atmosphere than barotropic models. Another advantage is that baroclinic models account for vertical variations in wind, temperature, etc. NOGAPS, OTCM, NORAPS, MFM, QLM, JTYM, and GSM are all baroclinic models.

7. **Spectral Models** A spectral forecast model is a model that uses continuous basis functions, such as trigonometric functions, to represent model parameters in space (usually horizontal space). Not all meteorological parameters are suitable for spectral representation. For example, precipitation is a discrete phenomenon that is difficult to represent in a spectral wave form. These discrete phenomena may be better represented using a finite difference method (i.e., grid point by grid point).

A few advantages of spectral methods are that they can be computationally efficient, provide for elimination of computational instability, and make some derived quantities easy to compute. Some disadvantages are that discrete phenomena are not suitable for spectral representation, computational efficiency decreases quickly as model resolution is increased, and output from spectral models must be transformed to a grid ("transform grid") for graphical display.

From a forecaster's standpoint, model resolution is more important than the computational methods used in a model because model resolution is related to the scale of weather phenomena that a model can represent. The following equation can be used to determine the distance X between grid points on the transform grid of a spectral model:

$$X = \frac{40{,}000KM}{4*(N+1)}$$

where N is the model truncation wave number. For example, in a T79 spectral model[2], we have X = 40000KM/(4*(79+1)) = 125KM. This is roughly equivalent to 1.25 degrees longitude spacing at the equator. Therefore, equatorial weather phenomena with wave lengths shorter than 500 km are not represented in the T79 spectral model.

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[2] The letter "T" in T79 indicates a triangular truncation, a type of wave number truncation currently used in spectral models.

If the maximum wind zone associated with a mature tropical cyclone has an average width of about 50 km, what is the minimum model resolution sufficient to resolve the maximum wind zone of a tropical cyclone? The answer is approximately a T800 spectral model. Fast computers, alternative computation methods and physics formulations are required in such models.

Currently even the fastest computers cannot run a T800 global model in a reasonable period of time. Therefore, for tropical cyclone structure studies, we must use high resolution fine mesh models to resolve tropical cyclone structure.

8. **Fine Mesh Models** Fine mesh models are high resolution models. Due to the large amount of computer processing time necessary to run these high resolution models, it is impractical to reduce the grid length over the entire globe or even one hemisphere. An alternative is to superimpose a fine mesh over one or more limited areas of the larger coarse mesh. This introduces the problem of providing boundary conditions on the periphery of the fine mesh during the course of the integration period.

9. **Boundary Conditions** Boundary conditions are the conditions must be satisfied along the boundaries of a limited domain (regional) model. Boundary values should be assigned in such a manner as to allow a smooth transition, for example, from the coarse resolution of a global model to the higher resolution of a regional model. The method used to derive the boundary conditions must guard against the introduction of severe changes in model variables along the boundaries.

10. **Boundary Layer** This is a transitional area between two distinct regions with different physical properties (e.g., air and water). In atmospheric modeling, the boundary layer is usually considered to be the layer of air adjacent to the Earth's surface. There are basically two ways to represent the boundary layer in a numerical prediction model. One way is to provide sufficient levels near the Earth's surface to resolve the boundary layer. Another way is to "parameterize" the processes occurring within the boundary layer so that the layer is represented with just one or two model levels.

11. **One Way Influence Models** These are fine mesh models which use information from a coarse mesh model, but do not influence the coarse mesh model. The simplest procedure is to interpolate the coarse mesh variables to the fine mesh boundaries at each time step of the coarse mesh. The coarse mesh points falling in the interior of the fine mesh are ignored in the fine mesh calculations, and the fine mesh calculations have no influence on the coarse mesh prediction.

The One Way Influence Tropical Cyclone Model (OTCM) is an example of a one way influence model because it uses information from NOGAPS, but it does not influence NOGAPS.

12. **Regression Methods** These are mathematical method is used in statistical weather data analysis and weather prediction. The most

commonly used regression methods consist of three iterative phases: problem definition, minimization and verification.

12.1 **Problem Definition** This is the phase in which the available data are collected and analyzed to determine the physical principles (e.g., environmental steering) governing a phenomenon (e.g., tropical cyclone motion). These physical principles can vary from something as simple as persistence extrapolated into the future to something as complex as relationships between dynamic fields and recurvature of a tropical cyclone. These relationships must be converted into mathematical equations.

12.2 **Minimization** This is a process to compute weights for various predictors in the mathematical equations developed in the previous phase. It begins with acquisition of a data set which contains data for the predictors and the predicted quantity. Relative weights for predictors are determined which minimize errors in predictions. For example, it may be determined that, given an equation which predicts 6 hour tropical cyclone speed of movement based on both 12 and 24 hour old speeds, assigning the heavier weight to the 12 hour vice the 24 hour average storm speed yields the best results. Once the weights are assigned, this one equation defines our statistical model.

12.3 **Verification** This is the phase in which the statistical model developed in the other two phases is tested with independent data (data other than that used to develop the model). Verification is accomplished by comparing results from the independent data runs with those of alternative methods. If the statistical model discussed above was developed using 1945-1979 tropical cyclone tracks, then an independent data set could be formed from 1980 tracks.

13. **Synthetic Tropical Cyclone Observations** These are synthetically generated observations which are intended to represent a tropical cyclone in a model analysis. Tropical cyclone warning positions are often used to help place the synthetic observations in the analysis. This process is commonly called "tropical cyclone bogussing".

At FNOC, the tropical cyclone bogus is a set of synthetic surface and upper-air observations to 400 mb. These observations are symmetric around the tropical cyclone warning center position with an observation at the center, four at 220 km, four at 440 km, and four at 660 km from the forecast center.

APPENDIX B

GLOBAL NUMERICAL WEATHER PREDICTION SYSTEMS

1. INTRODUCTION

Numerical weather prediction (NWP) systems are used to determine the future state parameters of the atmosphere by numerical integration of hydrodynamic equations from an initial state. NWP systems are "cybernetic" because they combine human and computer elements. The future of NWP systems depends on computer power, observation data amount and data analysis methods, efficiencies of computational methods, fresh understanding of physics, and rigorous mathematic formulations of these physics. The state-of-the-art computer program portion of a NWP system generally consists of four modules:

1.1 Data Analysis

The data analysis module provides equally spaced data from unevenly spaced observations (reported data), climatological information, and evenly spaced model output data. In some modules, data nudging procedures are used to extract information from data taken at asynoptic times (e.g., satellite soundings data and surface observations).

The quality of an automated analysis method depends on the initial data sampling rates and data coverage, information content in the data, data error sources (instrument and observation, coding and formatting, transmission, or human errors), quality control methods, spatial and temporal coherence of data and data errors, and dynamic consistency between data and an assumed balance state (or first-guess field).

Many operational data analysis procedures use full NWP model output as their first guess (for example, six-hour wind and thickness predictions), especially in regions where observations and climatological information are sparse. For forecasters, it is important to note that a model analysis is model dependent.

1.2 NWP Model Initialization

The purpose of NWP model initialization is to remove certain gravity waves from the NWP model initial data set. These gravity waves have several common characteristics. For example, they have small horizontal wavelength and vertical wavelength (small in terms of model horizontal grid distance and troposphere depth), short period (about 1 hour or less), and significant amplitude (about 1 mb surface pressure). These gravity waves can be misrepresented (aliasing), or can grow artificially in a NWP model; thus, they are often treated as "noise" in a NWP model initial data set. The method of model initialization is to eliminate the divergence due to a noise-like gravity wave (or wave mode) by adjusting the velocity and pressure fields associated with that wave. NWP model initialization techniques work extremely well for the dry portion of a model atmosphere that is located away from the equator.

NWP model initialization is done either within the analysis module or as a separate module which uses data produced by the analysis module. The choice of which type initialization to use is determined by local requirements.

1.3 NWP Model

A NWP model is a computer program system that includes application, database, communication, interface, scheduling and system programs. This computer program system contains model physics for the earth's atmosphere, and data flow representing data access and storage as well as computational procedures. The NWP model is designed to predict certain atmospheric state parameters, such as the 500-hPa (500 mb) height and the 925-hPa (925 mb) winds, from a set of well behaved (initialized) initial conditions and boundary conditions. The NWP model predicts variables such as height, winds, temperature and moisture distributions; however, local weather phenomena, such as precipitation amount (rain, snow or hail amount), local winds, fog and visibility, are obtained by using diagnostic formulas, other local numerical weather prediction models, or empirical methods which frequently make use of these NWP model prognostic parameters.

1.4 NWP Model Output

NWP model output data dissemination, display, discernment and interpretation are primarily driven by users' needs, and communication and display technologies. Possibilities include 2-, 3-, or 4- dimensional contour drawing, stability indicies and model output statistics (MOS). MOS is a practical approach to provide statistically significant relationships between model output data and historical meteorological data. In this way the NWP model output can be tailored for local weather forecasts, and local forecast accuracies can be enhanced. Model output interpretation is a talent that depends heavily on forecasters' experience and understanding of a NWP model.

2. MODELING TRENDS

It is important to notice that almost all of the techniques adopted in a NWP system are evolving. Several clear trends in operational global modeling have been observed:

(1) Homogenization of model ingredients (including data, model physics, and computational methods).

(2) Centralization of global NWP systems (e.g., the consolidation of European modeling efforts at the European Center for Medium-range Weather Forecasts) to take advantage of advanced computation and communication power.

(3) Increasing global NWP model resolutions from "coarse" to "fine". A fine resolution model can catch and represent more detailed structures and information embedded in a weather system than a coarse resolution model does. The main difficulty of adopting finer resolutions is that, as sampling scales are changed, smaller scale phenomena affect the model. For example, tropical cyclones will play an increasingly important role in global modeling as horizontal resolution approaches 50 km.

(4) Increased research effort in data utilization, model completeness (in terms of physics formulations and phenomena inclusions as well as model resolutions), model output interpretation and computational methods.

(5) Automation of data disseminations. More effort will be spent for formulating, testing, verifying, and evaluating of these automatic or semiautomatic procedures.

The following Table 1 compares four global NWP systems. Table 2 compares methods of initial specification of a tropical cyclone for these global NWP systems.

Table 1. Operational Global Weather Prediction System Ingredient Comparisons (Part 1 of 9)

Agency --	European Center for Medium-range Wea. Forecasts (ECMWF).	Fleet Numerical Oceano. Center, USA (FNOC).	National Meteor. Center, USA (NMC).	Japan Meteor. Agency (JMA).
Global NWP system name	ECMWF Global Model.	Navy Operational Global Atmospheric Prediction System (NOGAPS).	NMC Global Models: 1. 3-day aviation (AVN), 2. 10-day medium-range forecasts (MRF).	JMA Computer System for Meteorological Services (COSMETS, February 1988) consists of the Numerical Analysis and Prediction System (NAPS) and the Central Automated Data Editing and Switching System (C-ADESS).

Table 1. Operational Global Weather Prediction System Ingredient Comparisons (Part 2 of 9)

Agency --	ECMWF	FNOC	NMC	JMA
Analysis data	Global satellite data; Global free-data (AIREP, AMDAR, TEMP, PILOT); Oceanic (SYNOP/SHIP, PILOT/SHIP, TEMP/SHIP, DRIBU); Land data (SYNOP); TEMP,PILOT.	geopotential, horizontal velocity, dew point departure (specific humidity), TOVS satellite reports and DMSP SSM/I.	geopotential, horizontal velocity, relative humidity.	SYNOP, SHIP; DRIBU; Bogus data; TEMP, PILOT; AIREP; SATEM, SATOB; GMS cloud data; Australian PAOB.
Analysis levels and horizontal resolution	31 hybrid model levels.	18 layers, and 1.5° resolution. 10, 20, 30, 50, 70, 100, 150, 200, 250, 300, 400, 500, 700, 850, 925, 1000 hPa and surface.	2.14°long x 1.08°lat resolution. 10 hPa to surface.	16 levels (surface-10 hPa), 1.875° resolution. 192x97 grid points.

Table 1. Operational Global Weather Prediction System Ingredient Comparisons (Part 3 of 9)

Agency	ECMWF	FNOC	NMC	JMA
Analysis method	asynoptic obs are used. Departures of observations are calculated against a first-guess valid at the time of the observation. MVOI used for analysis.	initial quality control for data errors (instrument and human errors, or local circulations). MVOI usd for analysis. Upper air moisture data was analyzed separately (Rennick, 1989).	global data assimilation system (GDAS). Gandin complex quality control. Spectral Statistic Interpolation (SSI), variational 4-D data assimilation with control of gravity oscillation (divergence and surface pressure tendency).	quality control during decoding, pre-analysis and analysis stages; MVOI from surface to 100 hPa, spline-sine functional fitting method from 70 to 10 hPa.
First (or initial) guess	6-hour NWP model forecast.	6-hour NWP model forecast.	6-hour NWP model forecast.	6-hour NWP model forecast.
Tropical cyclone bogus in analysis cycle	temporarily not available.	every 6 hours in the lower troposphere.	yes.	every 12 hours in the entire troposphere.
Data assimilation frequency	6-hour (±3-hour window).	6-hour.		6-hour (00, 06, 12, 18 UTC), about 6 hours after map time

Table 1. Operational Global Weather Prediction System Ingredient Comparisons (Part 4 of 9)

Agency	ECMWF	FNOC	NMC	JMA
Analyzed parameter	surface parameters (snow depth, SST); mass and wind on 31 model levels from surface to 10 hPa; humidity surface-250 hPa.	mean sea level pressure.		mean sea level pressure; u, v, T, and RH, surface-300 hPa; u, v, and T, 250-10 hPa; height Z 1000-10 hPa. 10, 20, 30, 50, 70, 100, 150, 200, 250, 300, 400, 500, 700, 850, 1000 hPa, surface.
Intialization method	Non-linear normal modes (NNM) of free oscillation of the model atmosphere, first five vertical modes, diabatic.	NNM, first three vertical modes are used.	None. The analysis data is used directly as the forecast model initial condition (first four vertical modes are used).	NNM procedure is applied to all vertical modes whose eigen periods are shorter than 48 hours.

Table 1. Operational Global Weather Prediction System Ingredient Comparisons (Part 5 of 9)

Agency	ECMWF	FNOC	NMC	JMA
Prediction periods, variables and phenomena	3 to 10-day prediction. Synoptic- and certain meso-scale temperature, T; mixing ratio, q; horizontal velocity (u, v); surface pressure, p_s.	3- and 5-day predictions from 00 or 12 UTC data. Synoptic-scale T, q, vorticity, ζ, and divergence, D.		3-day for 00 UTC; 8-day for 12 UTC (daily); 15-day for 12 UTC (3 times/month). Synoptic-scale T, q, ζ, and D.
Prediction model and date of first operation	ECMWF T213/L31, 17 Sep. 1991.	NOGAPS Ver. 3.2, T79/L18, 1989.	MRF model, T126/L18.	Global Spectral Model (GSM8911), T106/L21, Nov. 1989.
Total horizontal wave numbers including the zonal mean	214 (T213) with reduced Gaussian grid representation.	80 (T79).	127 (T126).	107 (T106); Gaussian grid, 1.125°lat (grid number 320x160).
Approximate wavelength of a $4\Delta x$-wave at the equator	188 km.	506 km.	318 km.	377 km.

Table 1. Operational Global Weather Prediction System Ingredient Comparisons (Part 6 of 9)

Agency	ECMWF	FNOC	NMC	JMA
Vertical levels	31 (p_s to 10 hPa or earth's surface-30 km).	18 (p_s to 10 hPa).	18.	21 (p_s to 10 hPa).
Vertical coordinate system(s)	hybrid: terrain following coordinate (sigma) in tropo-sphere, pressure coordinate at upper levels.	hybrid (sigma and pressure).		hybrid (sigma and pressure).
Horizontal advection scheme	semi-Lagrangian method.	Eulerian spectral method.	Eulerian spectral method	
Vertical difference	non-interpolation, semi-Lagrangian vertical advection.	centered finite difference.		
Time difference	semi-Lagrangian semi-implicit.	semi-implicit.		semi-implicit.
Time increment	15 min.	15 min.		

Table 1. Operational Global Weather Prediction System Ingredient Comparisons (Part 7 of 9)

Agency	ECMWF	FNOC	NMC	JMA
Radiation (short/ long waves)	yes.	yes.	Lacis and Hansen (1974) / Fels and Schwarzkopf .	Lacis and Hansen (1974) short wave radiation flux is computed every 3 hours / long wave radiation flux is computed every 3 hours. and short wave (every hour).
precipi-tation	stratiform clouds can form in any number of layers. Mass flux scheme (momentum, heat and moisture transport by cumulus circulation).	large-scale precipita-tion and Arakawa scheme.	large-scale precipita-tion and Kuo scheme.	modified Kuo scheme for deep convection; Tiedtke scheme for vertical mixing processes of shallow convection.

Table 1. Operational Global Weather Prediction System Ingredient Comparisons (Part 8 of 9)

Agency	ECMWF	FNOC	NMC	JMA
Ozone and carbon dioxide	climatology	climatology monthly O_3, const. CO_2.	climatology	climatology
Boundary-layer process	surface fluxes of heat, moisture and momentum; three surface and sub-surface levels allowing for vegetation cover, gravitational drainage, capillarity exchanges, surface and sub-surface run-off, deep layer soil temperature and moisture).	yes.	Monin-Obukhov similarity theory.	surface fluxes of heat, moisture and momentum; Mellor and Yamada planetary boundary layer scheme; simple biosphere scheme (SiB) (Sellers et al., 1986; Sato et al., 1989).
Orography	terrain height (US Navy data set, 10 minutes of arc resolution).	yes.	silhouette(Mesinger *et al.*, 1988).	yes.

Table 1. Operational Global Weather Prediction System Ingredient Comparisons (Part 9 of 9)

Agency	ECMWF	FNOC	NMC	JMA
Gravity wave drag paramete-rization	yes.	yes.	yes.	vertical momentum deposits due to long (wavelength > 100 km) and short (10-km wavelength) waves are in the stratosphere and the troposphere, respectively.
Future changes	prognostic cloud scheme, possible increase in vertical resolution in the stratosphere.	FY1993: T159/L18 FY1994: T210/L30.		
Source and date of information	Dr. H. Böttger, ECMWF, Shinfield Park, Reading UK, 3 June 1993	Models Department, FNOC, Airport Rd., Monterey, CA, USA 93943, 10 May 1993	Dr. E. Kalnay, NMC, World Weather Building, 5200 Auth Rd., Camp Spring, MD, USA 20031, June 1993	Dr. Ken-ichi Kuma, JMA, 1-2-3 Otemachi, Chiyoda-ku, Tokyo, Japan 100, 26 May 1993

Table 2. Methods of Initial Specification of Tropical Cyclone in Operational Global Weather Prediction Systems (Part 1 of 4)

Agency	ECMWF	FNOC	NMC	JMA
Input data		large-scale environmental winds (T20 spectral truncation of analysis of first guess wind field, i.e. the first 20 zonal waves in analysis field), the tropical-cyclone location and vortex structure including the maximum speed, the maximum speed radius (MSR), a shape parameter for the speed beyond the MSR.	cyclone location and current track, size and intensity (central pressure, radius and pressure of outermost closed isobar, radius and speed of the maximum low-level wind, 15 m/s wind radius in the four geographic quadrants, and approximated height of the closed vortex circulation).	tropical cyclone (TC) location, center surface pressure and 15 m/s wind radius. The TC domain (TCD) is defined by empirical formula based on 15-m/s radius. Profiles of TC surface pressure (Fujita's formula), geopotential height and gradient wind are calculated in TCD. Surface pressure observations within TCD are used by least square fitting method.

Table 2. Methods of Initial Specification of Tropical Cyclone in Operational Global Weather Prediction Systems (Part 2 of 4)

Agency	ECMWF	FNOC	NMC	JMA
Bogusing field	none.	winds of a composited VR-vortex at 1000, 925, 850, 700, 500, and 400 hPa levels and 1000 hPa height plus the large-scale environment winds as steering.	mass in terms of the surface pressure.	Geopential height profile is defined by Frank's empirical formula (1977) that assumes the maximum positive temperatur e deviation is at 250 hPa. Gradient winds are computed from this geopotenti al profile.
Bogusing cyclone size.		30 and 50 kt wind radii.	15 m/s wind radius.	15 m/s wind radius.

Table 2. Methods of Initial Specification of Tropical Cyclone in Operational Global Weather Prediction Systems (Part 3 of 4)

Agency	ECMWF	FNOC	NMC	JMA
Bogusing sounding locations		13 bogusing soundings: 1 at the cyclone center, 4 at 220 km north, south east and west from the center, 4 at 440 km NE, SE, SW, and NW of the center, 4 at 660 km N, S, E and W of the center.		Bogus profiles are inserted in the lower troposphere up to 400 hPa. The geopotential and winds are superimposed on the first guess fields in the TCD.
Bogusing large-scale steering		the large-scale environment winds (T20).	selected background flow as steering flow.	no.
Lateral blend zone		size dependent.	size dependent.	the bogus profile and original guess field are smoothly connected near the TCD boundary.

Table 2. Methods of Initial Specification of Tropical Cyclone in Operational Global Weather Prediction Systems (Part 4 of 4)

Agency	ECMWF	FNOC	NMC	JMA
Tropical cyclone tracking		automatic (Hamilton's isogon method).	automatic (minimum wind speed and height, and maximum relative vorticity at 100 and 850 hPa levels).	n/a.
Future changes				
Source and date of information	Dr. H. Böttger, ECMWF, Shinfield Park, Reading UK, 3 June 1993.	Dr. J. Goerss, NRL, Airport Rd., Monterey, CA, USA 93943, 10 May 1993.	Dr. S. Lord, NMC, World Weather Building, 5200 Auth Rd., Camp Spring, MD, USA 20031, May 1993.	Dr. K. Onogi, JMA, 1-3-4 Otemachi, Chiyoda, Tokyo, Japan 100, 26 May 1993.

APPENDIX C

OBJECTIVE AID DESCRIPTIONS

1. JTWC OBJECTIVE AIDS

JTWC divides objective aids into six categories: extrapolation, climatology and analogs, statistical, dynamic, hybrid and empirical or analytical. The following is a brief discussion of the objective aids within each of these categories.

1.1 Extrapolation (XTRP)

Extrapolation techniques are used at JTWC for both track and intensity forecasting. Forecast speed, direction and intensification are computed by taking the difference between the current working best track position and the 12-hour-old best track position. The accuracy of XTRP is obviously dependent on the accuracy of the working best track positions. Thus, for weak and poorly defined circulations, the performance of XTRP will be poor, whereas for intense systems with an eye, the XTRP forecast should be quite representative of the actual past motion of the storm. Statistically, XTRP performs quite will for the first 12 to 24 hours, and can perform well for later forecast times if the synoptic situation is such that steady movement and intensification are expected.

1.2 JTWC Climatology and Analogs

The historical data base in the Northwest Pacific, is 1945-81, and 1900-90 for the rest of JTWC's AOR. The climatological and analog objective aids use subsets of this database.

1.2.1 Climatology (CLIM)

CLIM selects all historical storms that have best track positions that fall within a 6 x 6 degree box centered on the current position of the storm, and that occur in the month or months covered by the past 48 hours. If no historical storms satisfy both of these criteria, the time window is set at all 12 months.

CLIM then produces 24, 48, and 72 hour forecast positions by an unweighted averaging of all historical storm best tracks.

1.2.2 TYAN93

An analog forecast is a weighted average of the past motion of the current storm and a selected sample of historical tropical cyclone tracks. The historical data base is the same as that used by CLIM. Historical storms are included in the computation of a forecast if they are the best match of the past 12 hour and 24 hour motion vectors and have one or more best track positions that meet a date and time criteria. This aid produces a list of the top five matching storms along a straight or recurving track for 12 and 24 hour past motion vector matches and for a blend of the straight and recurving storms.

1.3 Statistical

A statistical objective aid applies regression techniques/predictions to a given situation based on a statistical characteristic of the current storm motion, past storm motion and intensity, or the surrounding environment. The following is a brief description of the statistical aids used at JTWC.

1.3.1 Climatology and Persistence (WPCLIPER or CLIP)

A statistical regression technique that is based on climatology, current position and 12-hour and 24-hour past movement. This technique is used as a crude baseline against which to measure the forecast skill of other more sophisticated techniques. CLIP in the Northwest Pacific uses third-order regression equations and is based on the work of Xu and Neumann (1985). This model consists of 12 regression equations, six of which are used to give predicted zonal speed in 12 hour increments, and the other six used to give predicted meridional speed in 12 hour increments. The resulting speed predictions are integrated to give forecast positions at 24, 48, and 72 hours.

1.3.2 Colorado State University Model (CSUM)

A statistical-dynamical technique based on the work of Matsumoto (1984). It actually consists of three sets of independent regression equations that can be used to generate the 24, 48, or 72 hour forecast position. The equation set used for a particular forecast depends on whether the present (for the 24 hour forecast) or forecast positions of the storm are deemed to be below, on, or above the subtropical ridge. This determination is made on the basis of the direction of motion over the preceding 24 hours according to the following definitions:

(1) below the ridge: set initially, unless 2) or 3) apply
(2) on the ridge: direction of motion 330 to 030 degrees
(3) above the ridge: direction of motion 031 to 120 degrees

Synoptic analysis and numerical prognosis inputs to the regression equations are interpolated 500 mb height values taken at + or - 40 degrees longitude and +35 and - 10 degrees latitude relative to the present or predicted location of the storm according to the following schedule:

(1) 24 hr forecast: current and 24 hour-old-analyses
(2) 48 hr forecast: current analysis and 24 hour prognosis
(3) 72 hr forecast: 24 and 48 hour prognoses

NOGAPS 200 mb heights are substituted for the 500 mb values for storms that are north of the ridge and have a wind intensity of greater than 90 knots. The 24 hour forecast equations also include the current and 24-hour-old position of the storm.

1.3.3 JTWC92

A statistical-dynamical technique based on the work of C. J. Neumann (Englebretson, 1992). Predictor parameters include current and 12-hour-old position of the storm, a version of WPCLIPER, deep layer mean analysis and prognostic fields, and regression coefficients needed to blend the output of numerous iterations of the statistical prediction technique employed to develop the track forecasts.

1.4 Dynamic

The following are brief descriptions of the dynamic aids used at JTWC.

1.4.1 NOGAPS Vortex Tracking Routine (NGPS)

This objective technique follows the movement of the vortex as analyzed and predicted in the NOGAPS 1000 mb wind field using an isogon fix method developed at Fleet Numerical Oceanography Center. A search for the vortex is conducted every six hours in the vicinity of the storm through 72 hours even if the vortex is temporarily lost.

1.4.2 One-Way Influence Tropical Cyclone Model (OTCM)

This technique is a coarse resolution (205 km grid), three layer, primitive equation model with a horizontal domain of 6400 x 4700 km. OTCM is initialized using six hour or 12 hour prognostic fields from the latest NOGAPS run, and the initial fields are smoothed and adjusted in the vicinity of the storm to induce a persistence bias into OTCM's forecast. A symmetric bogus vortex is then inserted, and the boundaries are updated by NOGAPS fields as the integration proceeds. The bogus vortex is maintained against frictional dissipation by an analytical heating function. The forecast positions are based on the movement of the vortex in the lowest layer of the model (effectively 850 mb).

This model is set up as follows:

(1) 3-layers: 1000-700, 700-400, and 400-100 mb
(2) horizontal resolution: 205 km
(3) approximate domain: 6000 km east-west by 4800 km
(4) initialized off the appropriate prognostic fields (usually six or 12 hr progs) from latest NOGAPS run.
(5) boundaries updated by NOGAPS field value every 12 hours during run.
(6) bogussed with a symmetric, medium-sized, deep, mass-balanced bogus vortex with size and intensity adjustable based on best track information.

The synoptic wind field in the vicinity of the current storm position is smoothed and adjusted to provide a steering that corresponds with 12-hour past movement to give OTCM an initial persistence bias. The bogus vortex is then added and model integration begins.

1.4.3 FNOC Beta and Advection Model (FBAM)

This model is an adaption of the Beta and Advection model used by NMC. This model combines steering based on smoothed NOGAPS deep layer mean (DLM) wind fields without an empirical "propagation" correction. The DLM mean wind field is computed using all NOGAPS pressure levels from 1000 mb to 100 mb, thus giving a deep definition of environmental steering. Maximum weighting is given to the 700 mb level. The DLM fields are also smoothed by retaining only NOGAPS spectral wavenumbers less than 18, or effectively, wavelengths greater than about 2000 km.

The steering is assumed to be horizontally uniform, and is computed by averaging smoothed DLM values at 400 km N/S/E/W of the current position of the tropical cyclone at each point in the forecast. New storm positions are generated in one-hour steps based on the total steering propagation velocity vector. The effective radius and inflow angles are recomputed with each time step, since they will vary as beta changes with latitude. A linear time interpolation is made between the appropriate DLM fields to provide smoother variation in steering with time. A persistence feature is included, which weighs 12-hour past motion out to the 12-hour forecast position using a cosine weighting function.

1.4.4 **Medium Beta and Advection Model (MBAM)**

This model is an adaptation of the FBAM model with the steering flow derived from the 850, 700 & 500 mb layers' weighted mean winds.

1.4.5 **Shallow Beta and Advection Model (SBAM)**

This model is an adaptation of the FBAM model with the steering flow derived from the 850 & 700 mb layer weighted mean winds.

1.4.6 **Japanese Typhoon Model (JTYM)**

The Japanese Typhoon Model is a limited-area, gridpoint model with the following specifications:

(1) 50 km horizontal resolution
(2) 109x109 gridpoint (approximately 5500x5500 km)
(3) Lambert conformal projection for storm latitude > 20N; mercator projection otherwise
(4) 8 vertical (sigma) levels
(5) boundaries updated by Japanese Global Spectral Model (GSM) once a day.
(6) provides forecast positions only out to 60 hours.

1.4.7 **NOGAPS Steering Model (NSM)**

The NOGAPS Steering Model(NSM) is being developed and tested at JTWC. It differs from FBAM in four important aspects:

1) It uses only 500 and 700 MB, unsmoothed windfields downloaded from FNOC via TYMNET. The data are digital and on a 2.5 X 2.5 degree grid.
2) No propagation component is added.
3) No persistence component is added.
4) Forecasts based on single-level steering are available (NSM7 & NSM5) in addition to a pressure-weighted layer average forecast (NSML).

The average steering at any time is computed by averaging windfield values around an annulus approximately centered on the storm, and approximately 6.25 to 8.25 degrees in radius.

1.5 **Hybrid**

The hybrid forecast aids used at JTWC are:

1.5.1 **Half-Persistence and Climatology (HPAC)**

Forecast positions are generated by equally weighting the forecasts given by XTRP and CLIM. Forecast positions are computed from a direct interpolation between corresponding forecast positions of XTRP and CLIM.

1.5.2 **Combined Confidence Weighted Forecasts (CCWF)**

An optimal blend of objective techniques, CCWF blends selected techniques (currently OTCM, CSUM and HPAC) by using the inverse of the covariance matrices computed from historical and realtime cross-track and along-track errors as the weighting function.

1.6 Empirical

The empirical forecast aids used at JTWC are:

1.6.1 DVORAK

An estimation of the tropical cyclone's current and 24 hour motion is made from the interpretations of satellite imagery (Dvorak, 1984).

1.6.2 Typhoon Acceleration Prediction Technique (TAPT)

This technique (Weir, 1982) utilizes upper-tropospheric and surface wind fields to estimate acceleration associated with the mid-latitude westerlies. It includes guidelines for the duration of acceleration, upper limits and probable paths of the cyclone.

2. NHC OBJECTIVE AIDS

The following, extracted from Sheets (1990), are brief reviews of the characteristics of objective aids used at NHC.

2.1 Extrapolation Aids

Extrapolation techniques are used for both track and intensity forecasting.

2.2 NHC Climatology-Based Objective Aids

All climatological aids used at NHC are based on the historical data base in the Atlantic, which consists of historical tracks from 1886 to the present. The climotological and analog (HURRAN) aids at NHC are very similar to those from JTWC.

2.3 Statistical

The statistical objective aids used at NHC are:

2.3.1 Climatology and Persistence (CLIPER)

CLIPER (Neumann, 1972) is a statistical model based on climatology and persistence. It consists of prediction equations that relate future zonal and meridional displacements of a tropical cyclone to a set of predictors. These predictors include initial and previous 12-hour positions, initial an previous 12-hour storm motion vectors, day number of the year (from 1 to 365) and the estimated maximum surface wind.

The prediction equations are derived using linear regression. The developmental data consist of a set of best tracks of tropical cyclones in the Atlantic Ocean, Caribbean Sea and Gulf of Mexico for the period 1931-70. Only tropical cyclones of tropical storm intensity or greater were included.

2.3.2 NHC83

NHC83 (Neumann 1988) is a statistical-dynamical model which uses the perfect prog method to derive statistical relationships between tropical cyclone motion and geopotential height fields. The developmental dataset included deep-layer mean geopotential height analyses for the period 1962-81 and Atlantic tropical cyclone tracks for the same period. Two separate regressions are performed for storms initially north or south of 25 N. The geopotential height grids are rotated so that the axes are along and perpendicular to the initial direction of motion of the tropical cyclone. When NHC83 is run operationally, the geopotential heights are obtained from the National Meteorological Center's (NMC) 18-layer, 80-wave global spectral model (the aviation model). The final NHC83 forecast track statistically combines the predictions using the geopotential heights with a

CLIPER-type prediction so that the model makes use of the initial motion estimate. The initial motion information is also used in the grid rotation.

Although no major changes were made to NHC83 during the verification period, the model which drives NHC83 has changed (Bonner, 1988). Prior to 1987, the 12-layer, 40-wave spectral model was used. Beginning in 1988, a correction to the geopotential height input was made to account for the differing biases in the 12- and 18-layer versions of the NMC spectral model.

2.3.2 **NHC-90**

NHC-90 is a statistical-dynamical model that is essentially an update to the NHC-83 model.

2.4 **Dynamical**

The dynamic aids used at NHC are:

2.4.1 **Sanders Barotropic (SANBAR)**

SANBAR (Sanders et al., 1975) is a barotropic-dynamical one level model that uses an equivalent barotropic vorticity equation to forecast a vertically averaged, pressure weighted, deep-layer wind field. The initial wind field includes the synoptic scale and the vortex scale, where the storm circulation is represented by an idealized axisymmetric vortex. The wind field is adjusted so that the initial motion of the vortex is approximately equal to the operational initial motion estimate.

SANBAR offers simplicity and efficiency in a dynamical model, and the barotropic assumption allows the initial motion vector to be included in a relatively straightforward manner. However, the skill of SANBAR is limited by the accuracy of the barotropic dynamics and synoptic analysis.

Several changes were made to SANBAR in 1985 (Goldenberg et al., 1987), including a modified analysis and increased horizontal resolution.

2.4.2 **Moveable Fine Mesh (MFM)**

The MFM (Hovermale and Livezey, 1977) is a multilevel baroclinic-dynamical model, where the model domain moves in order to remain centered on the storm. The model includes parameterizations of cumulus convection and boundary layer processes. Lateral boundary conditions are currently obtained from the aviation model, but were provided by the limited-area fine mesh (LFM) model prior to 1984. Before 1983, the storm circulation was determined from a simulation with an axisymmetric version of the model. The axisymmetric vortex was added to the large scale analysis to provide the model with initial conditions. Beginning in 1983, the vortex was determined from a three dimensional model run which included the variation of the Coriolis parameter with latitude. All of the MFM forecasts in the comparison included the three-dimensional vortex initialization. Unlike SANBAR or any of the other models discussed above, the MFM does not make use of the initial motion estimates in any way.

2.4.3 **Quasi-Lagrangian Model (QLM)**

The QLM (Mather, 1988) is also a multilevel baroclinic-dynamical model which includes parameterizations of physical processes. Lateral boundary conditions for the QLM are obtained from the aviation model, similar to the MFM, although the model domain does not move to follow the storm. It is not necessary to move the QLM domain since it covers a larger area than the MFM (about 4400 X 4400 km compared with 3000 X 3000 km for the MFM). The QLM uses 18 vertical levels and has a horizontal resolution of 40 km (compared with 10 levels and 60 km resolution for the MFM). The storm circulation is represented by an idealized vortex in gradient balance which is merged with a large scale analysis. Similar to the MFM, the QLM does not make use of the initial motion estimate.

2.4.4 Beta Advection Model (BAM)

The BAM model (Marks, 1989) can loosely be categorized as a barotropic-dynamical model, although it uses vertically averaged horizontal winds which were predicted from the NMC global spectral model. The basic idea of the BAM is that the storm track is determined by following a trajectory using the wind field described above, where the vertical average is from 850 to 200 mb. The trajectory includes a correction term to account for a component of storm motion due to the beta-effect (Holland, 1983).

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