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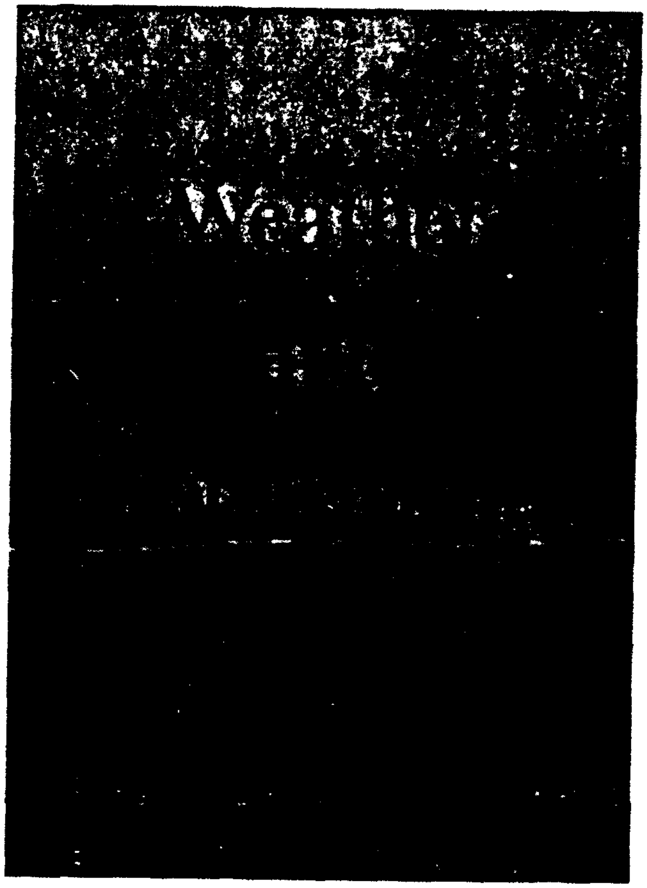

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An Evaluation of the Real-Time Tropical Cyclone Forecast Skill of the Navy Operational Global Atmospheric Prediction System in the Western North Pacific

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ABSTRACT

The meteorological quality and operational utility of the Navy Operational Global Atmospheric Prediction System (NOGAPS) in forecasting tropical cyclones is evaluated and it is shown that the model can provide useful predictions of motion and formation on a real-time basis in the western North Pacific. The evaluation was conducted during the 1990 operational testing of a procedure to improve the initial analysis or specification of tropical cyclones (TCs) in NOGAPS by the U.S. Navy Fleet Numerical Oceanography Center (FNOC). The NOGAPS TC analysis procedure generates synthetic TC observations based on operational vortex data (e.g., location and maximum surface wind speed) and then adds the observations to the observational data base with flags to force their assimilation. Results from the first year of testing were favorable, despite intermittent application of the procedure.

The meteorological characteristics of the NOGAPS tropical cyclone predictions were evaluated by examining the formation of low-level cyclone circulation systems in the tropics and vortex structure in the NOGAPS analysis and verifying 72-h forecasts. Analyzed circulations were found in the vicinity of developing TCs for nearly all cyclones during the operational test period. This finding implies that the model is "primed" for assimilating the synthetic observations and may be accurately simulating the large-scale environments favorable to TC formation. The analyzed TC circulations had greater than observed horizontal extent due to coarse grid spacing ($\Delta x \sim 160$ km) in the global model; however, the vortices, in general, were vertically stacked and maintained during the forecast by realistic amounts of thermodynamic forcing from the cumulus parameterization. Despite the large size of the NOGAPS TC vortices, the track forecasts were not overly biased with regard to track or speed. The operational utility of the NOGAPS track forecasts was analyzed through a comparison with the real-time runs of a baseline climatology persistence aid and with the best dynamical model used by the Joint Typhoon Warning Center, Guam. To ensure a realistic comparison of the forecasts and to improve the appearance of the global model tracks, a postprocessing adjustment procedure was employed that accounts for the observed initial motion and position. The adjusted NOGAPS track forecasts showed equitable skill to the baseline aid and the dynamical model. In fact, NOGAPS successfully predicted unusual equatorward turns for several straight-running cyclones. Overall, the adjusted NOGAPS track forecasts were judged to be competitive with other aids used by the operational forecasters at JTWC and it is suggested that global models may make important contributions to improving TC forecasting in the future.

1. Introduction

There is a growing interest among the major operational numerical weather prediction centers [e.g., the U.S. National Meteorological Center (NMC), the Japan Meteorological Agency (JMA), and the European Centre for Medium-Range Forecasts (ECMWF)] in directly forecasting tropical cyclones (TCs) with their global models (Kitade 1989). This undertaking is motivated by four factors. First, the horizontal resolution of the global models has steadily increased with computer technology advances.[1] Preliminary tests of pro-

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[1] As of July 1992 the operational models had the following spectral resolutions: ECMWF—T213; NMC—T126; JMA—T106; FNOC—T79.

totype high-resolution global spectral models (e.g., triangular truncation of 167 waves, or "T167") have demonstrated great promise for the accurate prediction of tropical cyclone motion and to some extent structure (Krishnamurti et al. 1989). Second, recent theoretical studies have suggested that the barotropic steering dynamics of tropical cyclone motion operates on scales resolvable by the current generation of global models (e.g., Fiorino and Elsberry 1989a,b). Third, several instances of credible tropical cyclone forecasts have been produced from earlier operational global models that had resolutions coarser than those in 1990 (e.g., Chan and Lam 1989; Hall 1987; Heckley et al. 1987). Finally, the long-range prediction of the synoptic-scale flow (and presumably the cyclone track) in global models will be superior to that from limited-area models (e.g., Hodur and Burk 1978) as these latter models require lateral boundary conditions that eventually distort the large-scale flow affecting the cyclone.

After an increase in the spatial resolution of the Navy Operational Global Atmospheric Prediction System (NOGAPS) in August 1989, several instances of excellent track forecasts (e.g., Hurricane Hugo) were observed. Furthermore, NOGAPS frequently developed low-level cyclonic circulations in the vicinity of tropical cyclones, even in data-sparse areas (Goerss et al. 1991). However, there were often differences between the positions of the model-generated and the observed cyclones, which confused operational users and appeared to degrade performance of the other track forecasting aids that relied on the NOGAPS fields. Accordingly, in June of 1990, the U.S. Navy Fleet Numerical Oceanography Center (FNOC) began a program to improve the ability of the global model to analyze and forecast tropical cyclones on an operational basis. The primary objective of the program was to enforce some degree of watch-to-watch consistency in the NOGAPS analysis and prediction of tropical cyclones by inserting synthetic TC data in the region of these storms.

This paper evaluates the performance of NOGAPS during the period 25 July through 24 December 1990 for 23 tropical cyclones (cyclone 09W–31W) in the western North Pacific. This period coincides with the field experiment phase of the Office of Naval Research Tropical Cyclone Motion Research Initiative, called TCM-90 (Elsberry 1990), and was the first operational test of the TC analysis procedure. Our evaluation addresses the ability of the model dynamics and physics to simulate the first-order features of the TC, such as a warm-core structure supported by realistic amounts of convective heating, and the performance with respect to other operational forecast aids. Accordingly, the NOGAPS tracks were postprocessed to make consistent comparisons with the operational products. Although this evaluation is limited to the FNOC global model forecasts in support of the Joint Typhoon Warning Center (JTWC), Guam, we believe the evaluation methodology and postprocessing procedures may have applicability at other numerical forecast centers.

Overview of the evaluation

The NOGAPS tropical cyclone analysis procedure consists of adding synthetic TC soundings to the observational database used by the global model analysis system. The synthetic TC observations are constructed based on all available vortex information [e.g., position, maximum wind speed, and radius of 30 kt (knot) (~15 m s^{-1}) winds] from the TC warning centers and are designed to aid the NOGAPS model in representing TC-like circulations on scales resolved by the global model.

The analysis of the meteorological aspects of the NOGAPS predictions was limited to 1) low-level cyclonic circulations (LLCC) activity, evidenced by closed circulations in the 925-mb streamfunction analysis, and tropical cyclogenesis; 2) vortex structure; and 3) track. All three are physically interrelated and the overall success of the model will depend on performance in each area. Each aspect (LLCC, structure, and track) is described in greater detail in the following discussion.

Tropical cyclogenesis was analyzed by following all LLCCs in each analysis and verifying 72-h forecasts (i.e., valid at the time of the analysis) during the five-month period. In addition, coincidence between NOGAPS LLCCs and observed cyclones was examined. Although we did not expect the model to be used necessarily as a tool for predicting the formation of tropical cyclones, the procedure for inserting synthetic observations of tropical cyclones is more likely to succeed if the first-guess field contains some background cyclonic circulation, that is, when deviations between the synthetic observations and the first guess are small (Goerss et al. 1991). Furthermore, if tropical cyclogenesis is truly a function of the large-scale (>5000 km) flow in the tropics (e.g., McBride and Zehr 1981), then a global model would have the potential for predicting such supportive environments. Additionally, the assimilated vortex relies on the diabatic forcing of cumulus convection for maintenance. This forcing depends on the thermodynamic structure of the environment so that convective activity and an LLCC prior to formation would aid the assimilation and help to sustain the vortex during the early stages of development. By examining the LLCC activity in NOGAPS, we measure both the degree of "resistance" (i.e., large observation/first-guess differences) to assimilating TC-scale observations and indirectly the model's prediction of some aspects of the large-scale flow in the tropics.

Three basic structural features of the NOGAPS TC circulations were qualitatively examined: 1) low-level (925 mb) wind and the radius of 30 kt (~15 m s^{-1}) winds; 2) vertical depth of the circulation; and 3) precipitation charts prepared once a day. Horizontal extent of the vortex and the magnitude of the winds in the r = 500–800 km annulus have been related to a self-propagation effect (e.g., beta drift) due to the gradient of absolute vorticity (Carr and Elsberry 1990; Fiorino and Elsberry 1989a). Thus, a positive correlation between biases in the NOGAPS forecasts to the right of the observed path (Northern Hemisphere) and excessive winds in the outer regions of the circulation could be useful in adjusting the NOGAPS synthetic TC observations. The vertical structure of the tropical cyclone is related to the level of synoptic-scale steering (Velden and Leslie 1991). For example, a shallow circulation would tend to track with the low-level flow and a consistently shallow NOGAPS cyclone might be expected to exhibit significant track biases. Precipitation measures the principal diabatic forcing on the tropical cyclone and is the key physical process that maintains the vortex. Location and intensity of precipitation around the NOGAPS TC vortices can help gauge the quality of the cumulus parameterization; weak rainfall or poor location would indicate serious deficiencies in the scheme (Puri and Miller 1990).

While genesis and structure are mainly related to the meteorological aspects of NOGAPS and TC analysis procedure, the track prediction is of primary concern to the tropical cyclone forecaster. The NOGAPS TC positions were extracted from the operationally available analysis and forecast fields. However, large differences were found between the global-model initial positions and those from JTWC due to operational limitations on when the synthetic observations were applied and communication limitations between FNOC and JTWC. Furthermore, the forecasts generated directly from the NOGAPS fields would not be available to JTWC until after the warning was issued. Therefore, a postprocessing procedure was employed to remove the initial position discrepancy and to improve timeliness by providing a track valid at the same time as the other aids. Both the NOGAPS raw and postprocessed tracks were evaluated in terms of mean forecast error and cross-track and along-track biases that indicate whether the forecasts are to the right or left of the observed track and whether the model position is behind or ahead of the verifying position. Additionally, the track errors were stratified for cases with and without insertion of synthetic TC observations and with respect to track types (e.g., recurve versus straight moving) to understand how model skill varies with synoptic conditions. In general, the NOGAPS track forecasts exhibited skill comparable to that from the other operational aids.

2. NOGAPS and the tropical cyclone analysis procedure

NOGAPS consists of a multivariate optimum interpolation (MVOI) analysis and an 18-layer global spectral prediction model with a triangular truncation of 79 waves (T79). This spectral resolution is equivalent to a horizontal spacing of approximately 160 km in a gridpoint model. The MVOI is performed on the 1.5° Gaussian grid (Goerss and Phoebus 1992). The model features a full suite of parameterized physical processes, including the Arakawa–Schubert cumulus scheme (Arakawa and Schubert 1974), and has been observed to be thermodynamically responsive to disturbances in the tropics. See Hogan and Rosmond (1991) for more details regarding the model. From a modeling viewpoint, NOGAPS should be capable of predicting at least the larger-scale component of the tropical cyclone vortex, providing this component is not strongly forced by smaller scales within the cyclone inner core. Barotropic modeling studies have indicated that such a small-to-large-scale forcing is of minimal importance to the forecast track exclusive of high-frequency track oscillations (e.g., Fiorino and Elsberry 1989a,b). This caveat notwithstanding, the primary goal of the tropical cyclone assimilation procedure is to enable the MVOI to depict the NOGAPS-resolvable component of the tropical cyclone in a consistent and reliable manner.

The NOGAPS tropical cyclone analysis strategy is patterned after that of ECMWF (Andersson and Hollingsworth 1988). Synthetic soundings are constructed in the vicinity of the storm based on observed vortex parameters and then are added to the operational observational database with flags to force their acceptance by the MVOI analysis. The MVOI was not modified to account for smaller scales as proposed by Puri and Lönnberg (1991), for example, reducing the search radius and changing the error structure functions. The soundings are generated only for cyclones with maximum wind speeds exceeding 34 kt ($\sim$17 m s^{-1}).

In accordance with the steering model of tropical cyclone motion, the synthetic observations are assumed to be the sum of 1) a large-scale, environmental flow; and 2) a symmetric, cyclone-scale vortex. The environmental flow is taken from spectrally truncated fields where only the first 20 waves are retained (T20 vice T79). Although this truncation essentially eliminates tropical cyclone–scale features, small contributions of a vortex to even the largest waves may remain because of the nature of the spectral basis functions used in the model.

The symmetric vortex component of each synthetic sounding is derived from a Rankine vortex in gradient balance whose structure is controlled by three parameters: 1) the maximum wind speed; 2) the radius of maximum wind; and 3) an exponential factor that governs the flow beyond the radius of maximum wind. During the evaluation period, the maximum wind speed was taken from the warning message and the radius of maximum wind and the exponential factor were fixed at 50 km and 0.6, respectively. Preliminary testing prior to the 1990 operational test showed that these settings led to unrealistically strong vortices in the context of a relatively coarse global model. To counteract this problem, the vortex component of the synthetic TC observations was arbitrarily reduced by 25%. This reduction was partially justified because the Rankine vortex is representative of observed tropical cyclones and thus contains scales much smaller than those resolved by the NOGAPS model as discussed by Fiorino and Elsberry (1989b). As of 1991, the radius of maximum wind and the exponential factor are derived from the radius of 30 kt (~15 m s^{-1}) and 50 kt (~26 m s^{-1}) winds to more closely match the synthetic vortex observations to observed cyclone structure parameters (Goerss et al. 1991).

Synthetic soundings are generated at 13 points around the cyclone, as depicted in Fig. 1, and consist of wind and height at 1000 mb and winds at 925, 850, 700, 500, and 400 mb. The symmetric vortex component of the synthetic sounding is reduced in the vertical to simulate the warm-core structure of the tropical cyclone (1.0 at 1000 mb to 0.65 at 400 mb). No observations are produced above 400 mb, so that the upper-level structure must be generated by the model. Plans are under way to extend the soundings upward to at least 200 mb.

Prior to November 1990, the generation of the synthetic observations and their admission to the NOGAPS database required human intervention at FNOC and some time periods were missed. This initiation process, and the intermittent nature of tropical cyclone activity, reduced the temporal consistency of the TC analysis. However, in November 1990 JTWC began transmitting a special message to FNOC that automatically activates the procedure. This message is written in a new World Meteorological Organization format designed for the exchange of tropical cyclone position and structure data between cyclone forecast offices and the numerical forecast centers worldwide, and these data are now distributed on the Global Telecommunication System via NMC (Lord 1992, personal communication). The automated system has improved the reliability of the NOGAPS tropical cyclone analysis and should improve the consistency of the vortex structure throughout the life cycle of a cyclone.

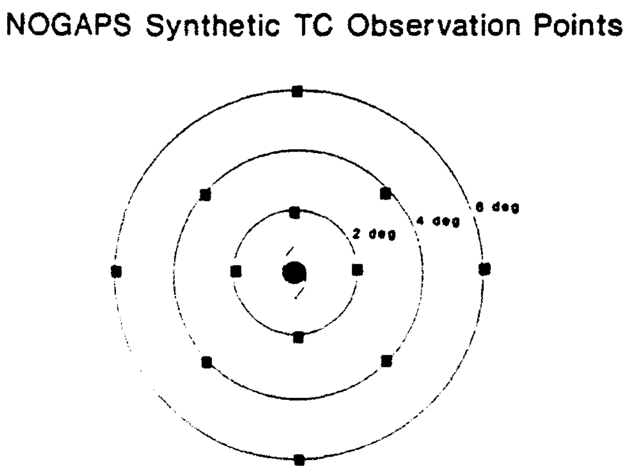


FIG. 1. Location of the 13 synthetic observation points (squares plus the center denoted by the hurricane symbol). Each ring is 2° from the center.

During the evaluation period, for operational reasons at FNOC, the synthetic tropical cyclone observations were analyzed only during the "posttime" run of the MVOI, which begins approximately 9 h after synoptic time. The advantage of this approach is that the delay allows observations that did not reach FNOC in time for the "real-time" analysis (+2.5 h after synoptic time) to be included in the data assimilation process. The real-time analysis provides the initial conditions for the NOGAPS forecast integration. The disadvantage is that synthetic TC soundings for a 0000 UTC cyclone would not appear until the subsequent 1200 UTC real-time analysis. Thus, the vortex must be carried forward by the model during the two intervening 6-h forecasts/analyses of the assimilation cycle. Although some initial position discrepancies resulted, we did not observe sudden changes in the analyzed vortex position or structure, which implies that the NOGAPS model was fairly successful in maintaining the vortex during the assimilation.

3. Data and vortex tracking

This evaluation is based on NOGAPS field data taken in real time and simulates the conditions under which the tracks would be calculated and used by JTWC. The NOGAPS solutions on sigma coordinates were interpolated to pressure levels and then specified on the standard FNOC 2.5 × 2.5° spherical grid. Although this resolution is coarser than the model Gaussian grid (~1.5°), the smallest wave resolved by the T79 model has a wavelength of 4.5°. Thus, little spectral information is actually lost during the projection to the FNOC standard spherical grid. Field data on a smaller subgrid covering the western North Pacific (15°S to 60°N, 60°E to 160°W) were compressed and formatted for communication either as a text message or as a binary file. These data were then transferred to a microcomputer where all track processing and genesis/structure analysis were performed.

Random-access field data files were constructed from the compressed data for every run of NOGAPS (twice daily) during the evaluation period and contained 1) sea level pressure, winds at 925, 850, 700, 500, 400, 300, and 200 mb, and a deep-layer tropospheric mean at t = 0, 24, 48, and 72 h; 2) sea surface temperature; 3) analyzed marine surface winds; and 4) precipitation every 12 h from t = 12 to 72 h for a total of 81 fields per run of NOGAPS. The entire set (about 160 files), including derived diagnostic quantities, requires about 15 MB of disk space.[2]

The relative vorticity at 925 mb was used to define the cyclone center for tracking because this level is representative of the vertically averaged flow in the planetary boundary layer. Comparison of circulation cen-

[2] These data and the decoder/database software are available upon request from the first author.

ters defined from objective streamline analyses showed a good correspondence to the vorticity centers, particularly after the cyclone reached tropical storm strength. Although other definitions of the storm center (e.g., minimum of surface pressure or streamfunction) may be equally valid, the coarse resolution of the model and the data grid implies an uncertainty in the extracted position that is larger than the expected differences among alternate center definitions.

Grid points with relative vorticity exceeding a threshold value of 2.0×10^{-5} s^{-1} were identified over the entire data grid and then a position between the grid points was calculated using Stirling's interpolation formula (Gerald and Wheatley 1984). The position located within 2° of the observed position was identified as the NOGAPS initial TC center. The observed initial position was taken from the message which JTWC submits to FNOC to initiate the running of their TC forecast aids. The search zone expands in time and is centered on the latest position (e.g., the 48-h center is based on a search from the 24-h forecast position) to handle recurving and/or accelerating cyclones. If no center is found, the TC is assumed to have dissipated. No special action is taken over land points.

In summary, the data in this study consisted of NOGAPS field data, the derived track forecasts, the real-time output from the other aids used by JTWC, and the operational "working" best track (Guard et al. 1992) for verification.[3] Our evaluation should provide an operationally realistic analysis of the tropical cyclone forecast skill of the global model.

4. Results

During the 5-month evaluation period of 25 July through 24 December, 23 tropical cyclones occurred in the western North Pacific—4 supertyphoons [maximum sustained winds ≥ 130 kt (~67 m s^{-1})], 12 typhoons, and 7 tropical storms. Track types of storms lasting longer than 24 h included 8 straight runners, 8 recurvers, and 3 cyclones tracking equatorward for a significant portion of their existence. Figure 2 shows a time line of tropical cyclone activity and when the synthetic TC observations were assimilated. Cyclones tended to occur in sets of two or more in association with an intensification and subsequent breakdown of large (>1000 km in horizontal extent) and deep monsoon troughs. The ability of the model to simulate this large-scale trough may be important when attempting to extrapolate skill and forecast rules to future seasons. While most NOGAPS TCs were influenced by the synthetic TC observations at some point in their life cycle, there were periods of 12 to 72 h, particularly in the early stages, when the NOGAPS-analyzed TCs were based only on actual observations and global model forecasts. Stratification of 72-h track forecast skill by the presence or absence of synthetic TC observations in the initial analysis will be presented in section 4e.

a. LLCC activity and tropical cyclone formation

Model performance was first analyzed in terms of the formation and maintenance of LLCC in the tropics (0° to 25°N) and the association of LLCCs with TC development. The purpose of the analysis was threefold. First, LLCC formation and maintenance is related to the quality of the NOGAPS physical parameterizations and the accuracy of the large-scale prediction in the tropics as TC genesis is strongly linked to the large-scale flow (McBride and Zehr 1981). While a consistent pattern of LLCC formation prior to TC development would not, in and of itself, validate the quality of a particular physics package, a lack of LLCCs, especially in those environments in which tropical cyclones were observed to have formed, would suggest a thorough review of the model physical parameterizations, starting with cumulus convection (Puri and Miller 1990). The second purpose of the analysis was to measure the "susceptibility" of NOGAPS to the assimilation of tropical cyclone observations. The MVOI performs an analysis by adjusting a first-guess field (i.e., a 6-h forecast) to differences between observations and the first guess. A small region of large differences would either be filtered out, depending on the forecast error covariances, or result in unrealistic changes over a larger area by aliasing (Puri and Lönnberg 1991). Thus, a model that does not form LLCCs in the tropics would be less capable of assimilating TC-like observations. Third, cyclone formation in NOGAPS may have some operational utility if used as an indicator of significant changes in the large-scale flow. In fact, toward the end of the 1990 typhoon season, JTWC began using NOGAPS together with satellite imagery loops to anticipate TC development (Goerss et al. 1991).

The LLCC analysis was performed by subjectively locating and numbering all closed cyclonic circulations and troughs in the NOGAPS 925-mb wind analysis and the overlaid verifying 72-h forecast in the tropics (equatorward of 25°N). The 72-h forecast was used to examine the long-range predictive capability of the NOGAPS model and as an internal consistency check between the model and analysis. Systems located within ±5° of each other, in both the analysis and verifying 72-h forecast, were considered to be the same feature. The intensity and areal extent of the circulation were not considered in tagging the features as the purpose was to understand the basic quality of the NOGAPS analysis and forecasts prior to the assimilation of the synthetic TC observations. The formation, decay, and merging of the LLCC systems were analyzed through

[3] The postanalysis best track was not available when the error statistics were generated. However, the operational working best track uses the same objective best-track routine and is also adjusted by the JTWC forecasters during the warning process in a similar manner as the postanalysis best track is produced. Differences between the working and postanalysis best track have been found to be small and will not change the overall sense of our results.

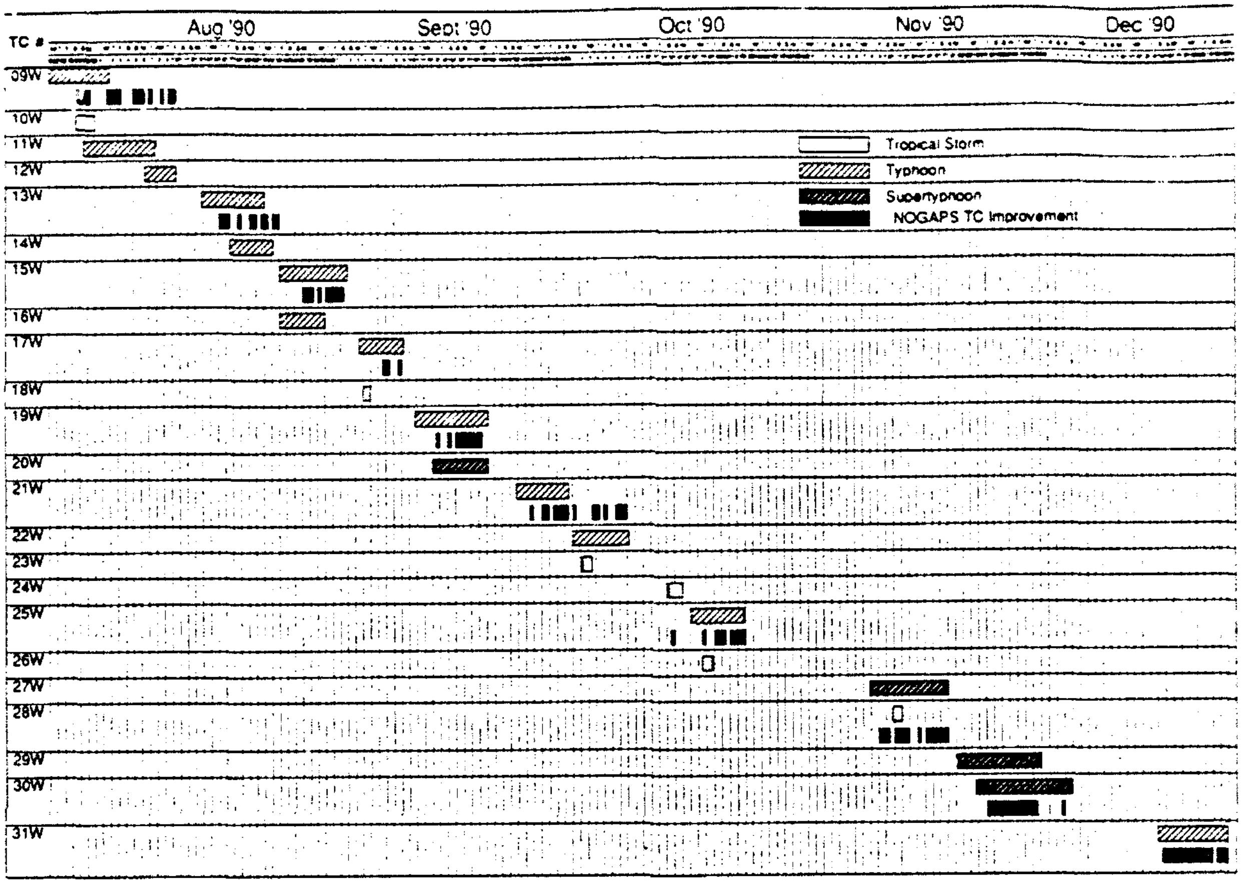


FIG. 2. Time line of tropical cyclone activity and NOGAPS TC analysis during the evaluation period of 25 July–24 December 1990 in the western North Pacific. Time (in days) runs in the x direction and cyclone number in the y direction. The hatched/dot-filled boxes represent the cyclones of various intensities and the solid bars are periods when the TC synthetic observations would impact the analysis.

a time line as illustrated in Fig. 3. The TC genesis point, marked on the figure for those LLCC systems that developed into a cyclone, is defined as the time when JTWC transmitted their first request to FNOC to execute the TC forecast aids.

The JTWC forecasters typically start running the aids before they issue a tropical cyclone formation alert (TCFA). The TCFA defines a latitude/longitude box in which a suspect cloud cluster is expected to form into a tropical depression in the next 24 h. Running the aids prior to the TCFA gives the JTWC forecasters time continuity in preparing the track forecast scenario (Guard et al. 1992) as the system goes into a warning status. In 1990, the average lead time between the TCFA and the first warning was 12.5 h (JTWC 1990). Thus, the quasi-operational TC genesis point may precede the actual point of genesis. Furthermore, an LLCC in the NOGAPS analysis or verifying forecast at this point could have been produced only from existing observations and/or generated by the model.

A total of 61 distinct LLCCs were found in the period 26 July–26 December 1990. Of those, eight were forecast at 72 h, but did not appear in the verifying analysis (a false-alarm rate of 13%), whereas four appeared in the analysis, but not in the forecast. More significantly, coincident LLCCs appeared in the 72-h forecast on average 24 h *before* the LLCC in the verifying analysis. That is, most of the LLCCs were developed by the model before they were analyzed.

This comparison does not verify how well NOGAPS reproduces observed levels of LLCC activity (except for TCs) as we did not have access to satellite and/or synoptic data. Rather, the comparison measures internal consistency, or how well the model internally simulates the development of low-level circulations using its own dynamics and physics, and presumably that of the large-scale tropical atmosphere. The modest false-alarm rate and the large number of LLCCs (23 of 53 analyzed LLCCs became TCs) suggest that NOGAPS is active in the tropical western North Pacific and should be able to assimilate the synthetic TC soundings without excessive shock or filtering of the vortex.

A more detailed evaluation of LLCC activity prior to observed TC formation is given in Fig. 4, which shows the time difference between the identification of the LLCC and the first JTWC TC aids request. An

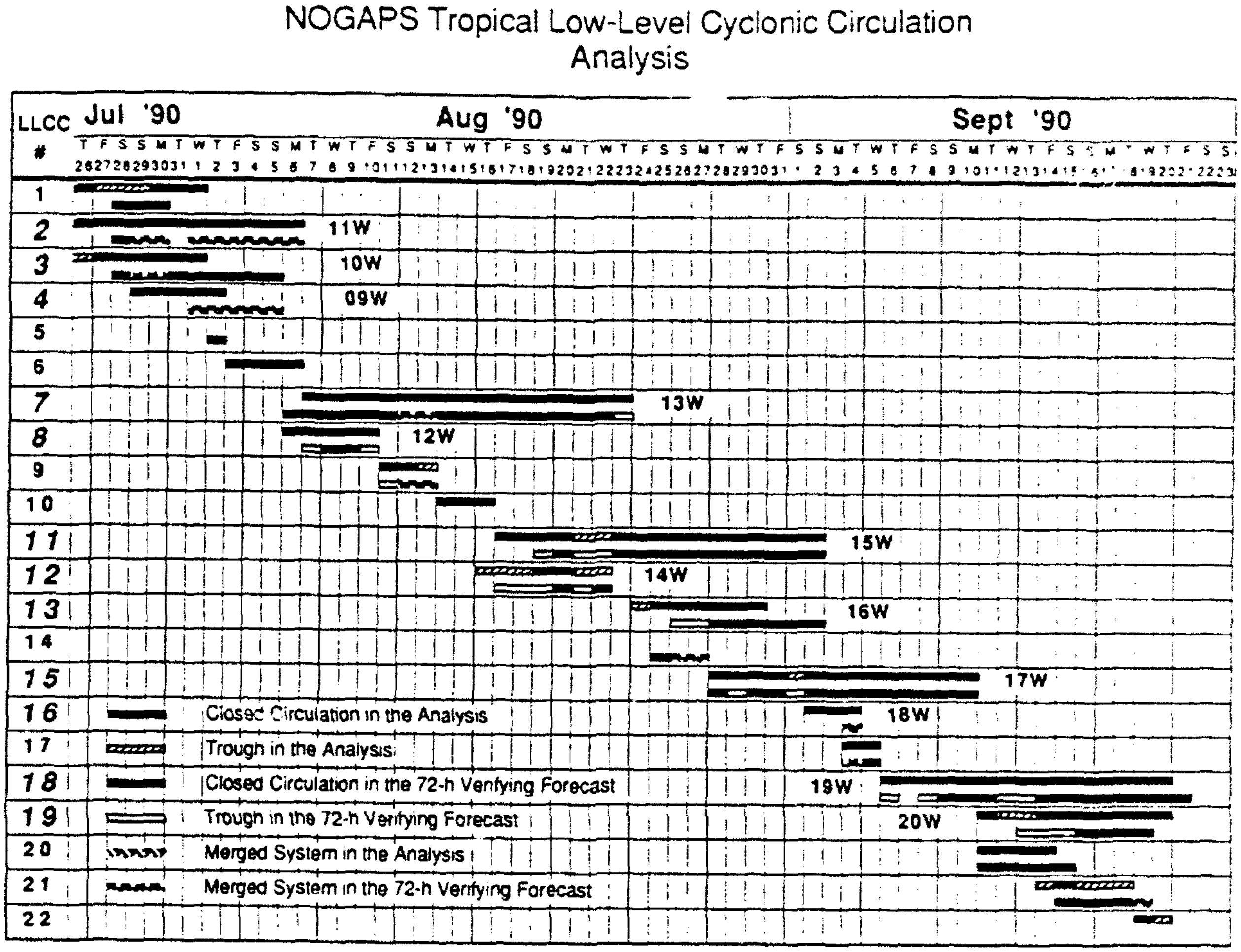


FIG. 3. Sample of the time line used to analyze NOGAPS LLCC activity. Time (in days) runs in the x direction and LLCC number in the y direction. LLCCs that developed into TCs are marked with the cyclone number and the operational genesis point is identified by the vertical line with triangular ends.

LLCC was present in the analysis for all but one case (22/23, or 96% coverage) and in the verifying 72-h forecast (a 3-day forecast that an LLCC would form near the genesis point) for all but three cases (20/23 TCs or 87% coverage). Also, note that an LLCC was present in some cases many days before genesis (e.g., cyclone 29W—11.5 d). The classification of the LLCC at the genesis points is given in Table 1. Note that the LLCC was closed in a majority of the cases (16/23) and that the NOGAPS analysis was more accurate (fewer missed and merged systems) than the 72-h forecast, as expected.

b. TC structure

TC structure was qualitatively evaluated using daily maps of streamlines and isotachs at the 925-, 500-, and 200-mb levels, and of precipitation rate. We examined the NOGAPS analysis and forecasts at t = 24, 48, and 72 h. The purpose was to determine how well the synthetic TC soundings were assimilated and the synoptic or first-order realism of the global model TC vortex (e.g., a nearly symmetric, warm-core cyclonic circulation). At the outset, we did not expect the model to produce tropical cyclones verifiable against observed structures (McBride 1984). A more quantitative analysis would be appropriate, however, when the NOGAPS TC analysis procedure employs more vortex parameters and model resolution is increased.

Figure 5a shows the analyzed 925-mb flow at 1200 UTC 16 September 1990 for two cyclones—supertyphoon 20W (max wind of 130 kt or ~67 m s^{-1}) south of Japan and typhoon 19W (max wind of 75 kt or ~39 m s^{-1}) in the South China Sea. As expected, the NOGAPS MVOI analysis did not reproduce the observed intensity. Note that the radius of 30 kt (~15 m s^{-1}) winds is asymmetric and considerably larger (7°–12°) than typically observed (2°–4°) (Williams 1986) and that the maximum winds (>40 kt ~21 m s^{-1}) in 20W are located 5° from the center. In the 72-h forecast (Fig. 5b) valid at 1200 UTC 19 September 1990, the vortices have not weakened during the fore-

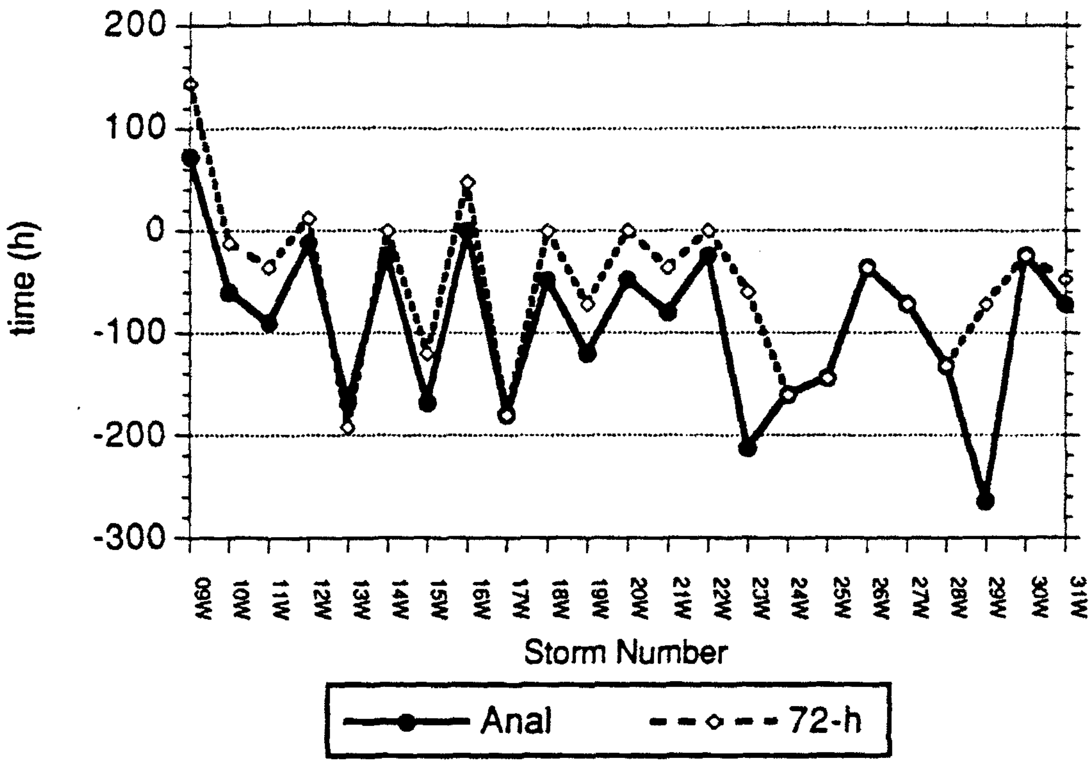


FIG. 4. Time lag between the first appearance of the developing LLCC in the NOGAPS analysis and verifying 72-h forecast and operational TC genesis defined by the time when JTWC issued their first request for running the TC aids. A negative value means the LLCC appeared before genesis.

cast, but the asymmetries have changed with enhanced flow southeast of the center for 19W and reduced winds over the southern islands of Japan for 20W. This change is related to enhanced friction over land and topographic effects in the global model.

It would be fair to conclude that the NOGAPS low-level vortex structure is not very realistic. Theoretical studies of TC motion would suggest that the model cyclone may have been expected to deviate significantly from the large-scale steering due to propagation effects (e.g., "beta drift") (Carr and Elsberry 1990). However, NOGAPS tracks for both cyclones were excellent. Perhaps the cyclone size "scales" with the model and the scales it supports, or the cyclone motion dynamics have been correctly compensated by the large-scale flow or vortex asymmetries. Regardless of these and other possible explanations, the issue needs to be analyzed in greater detail, particularly when making adjustments to the TC analysis scheme.

TABLE 1. Classification of the LLCC at the time of the genesis. "Closed" refers to a closed circulation as defined by the objectively drawn streamlines; a "trough" is an area of cyclonic turning; and a "merged" system results from the consolidation of two separate systems.

LLCC classification	Analysis	72-h forecast
Not present	1	3
Closed	16	16
Trough	5	2
Merged	1	2

The NOGAPS cyclone vortex was, in general, vertically stacked in the low and midtroposphere, and the strength and size decreased with height as expected of a warm-core system; however, an upper-level anticyclone or outflow jets were seldom present at 200 mb (not shown). This finding is consistent with the structure implied by the synthetic TC soundings in which observations are limited to 400 mb and below. Despite the lack of clearly defined outflow channels, the vortex remained vertically stacked below 200 mb during the forecast. This implies that the vertical motion forced by the cumulus convection was successful in maintaining vortex cohesion.

The precipitation for the 19W/20W case is given in Fig. 6. The rain rates were obtained by accumulating convective and large-scale (resolvable) precipitation over a 12-h period and expressed as a rate in centimeters per day. The convective component was much larger than the large-scale component around the NOGAPS TC vortices. The concentration of rainfall at points around the cyclone centers is more a consequence of the coarse resolution of the data grid rather than an indication of some model deficiency. Large rainfall rates in the vicinity of the cyclone center and occasional eyelike patterns (note the minimum around the center of 20W in Fig. 6a) were consistently produced by the model. While this global model cannot resolve the dynamics of eye formation, the qualitatively observation of eyelike patterns is noteworthy and may be worthy of further analysis. We also found cases where the rainfall rate was greater for strengthening cyclones than for decaying storms, but in general the maximum precipitation rates were on the order of 5–15 cm d^{-1}. These rates are comparable to those from various versions of the ECMWF global model as discussed by Bengtsson et al. (1982) and Puri and Miller (1990). Although instantaneous rainfall rates can be higher than 100 cm d^{-1} in a tropical cyclone, Frank (1977) has shown that composite rain rates, averaged over 2° latitude annuli, range from 10 cm d^{-1} in the inner core to 3 cm d^{-1} outside 2°. This averaging area is similar to the resolution of the model. Thus, it would appear that the NOGAPS physics is providing sufficient thermodynamic forcing to maintain the NOGAPS-resolved component of the vortex. Sufficient forcing is crucial to the performance of the model because 1) the cyclone must be sustained during the assimilation cycle and between breaks in the insertion of synthetic cyclone soundings; and 2) the assimilation is greatly improved if the model develops and maintains circulations that are in close agreement with the synthetic observations (Puri and Miller 1990; Goerss et al. 1991). Although the structure of the NOGAPS TC vortices cannot be considered realistic when compared to observed cyclones, the model is able to resolve and forecast the first-order structural features of the tropical cyclone and this capability may be sufficient for first-order track prediction.

c. *Track forecast analysis*

The most common measure of track forecast skill is the mean position or "forecast" error, which is simply the great circle distance between the observed and forecast position. Although a mean error can give no guidance on how to use a model in a specific situation, a small value signifies that the model has a greater likelihood of making a superior track forecast. This skill is especially important when the official forecasts are evaluated by the same score. Moreover, a mean forecast error that is better (i.e., lower) than climatology/persistence gives incentive to the modeler to improve the aid and to carry out a more detailed analysis to reveal specific model strengths and weaknesses for various track and synoptic conditions.

More important measures of skill to the operational forecaster are speed and track biases, that is, metrics that indicate whether a track forecast tends to be behind/ahead or to the right/left of the actual cyclone track. One way to measure these biases is to decompose the forecast error into cross-track (CT) and along-track (AT) components relative to the verifying track (Tsui and Miller 1988) as illustrated in Fig. 7. The CT error is related to path skill, whereas the AT error is related to the speed of the predicted track. Unfortunately, the cross-track and along-track errors are not independent because a large and negative along-track error (slow) will always imply a smaller cross-track error. That is, the slower the model, the smaller the track error because in the limiting case of a no-motion forecast, the forecast would have a large AT error and no CT error. Thus, statements regarding track skill and biases must be weighted against the magnitude and biases in the along-track error.

To give operational context to the results, we compared the NOGAPS track forecasts (raw and postprocessed) to two other aids: 1) the "no-skill" climatology and persistence aid (CLIP; Xu and Neumann 1985); and 2) the one-way influence tropical cyclone model (OTCM; Hodur and Burk 1978), a dynamical model with consistently superior long-range (48–72-h) skill (Tsui and Miller 1988). The OTCM has coarser horizontal ($\Delta x = 205$ km) and vertical resolution (three layers) than NOGAPS ($\Delta x \sim 160$ km and 18 layers). Further, the OTCM contains no physics other than a center-following, specified heating function to maintain the vortex during the integration. Despite the model's relative simplicity, the OTCM has been the best long-range track aid in the western North Pacific during the 1980s (Tsui and Miller 1988). The CLIP model is used to gauge forecast difficulty in that low CLIP errors imply consistent, climatological tracks and presumably easier storms to forecast. Of course, all climatological storms are easy to forecast in hindsight; nevertheless, CLIP has been used as a standard to judge meteorological skill in all TC basins (Pike 1985).

The initial position errors as a function of TC intensity category (Table 2) are generally large ($\sim 1.5°$) overall and decrease with increasing intensity as the vortex becomes better defined and as there is a greater likelihood that the synthetic TC observations were assimilated (most of the gaps in the TC analysis occurred in the beginning of a cyclone, see Fig. 2). The large errors also reflect the absence of TC analysis during the real-time analysis. That is, error was associated with "carrying" the vortex through the two 6-h forecasts/analyses of the assimilation cycle, and into the real-time analysis/forecast run from which the tracks were derived. Application of the TC analysis to the real-time analyses should reduce this initial position error.

d. *The NOGAPS track postprocessing procedure*

Unfortunately, JTWC operating procedures, and requirements on when the warning is issued, make it impossible to compare the operational results of the NOGAPS and OTCM dynamical models in a scientifically rigorous manner, that is, forecasts starting from identical initial conditions and vortex parameters. The

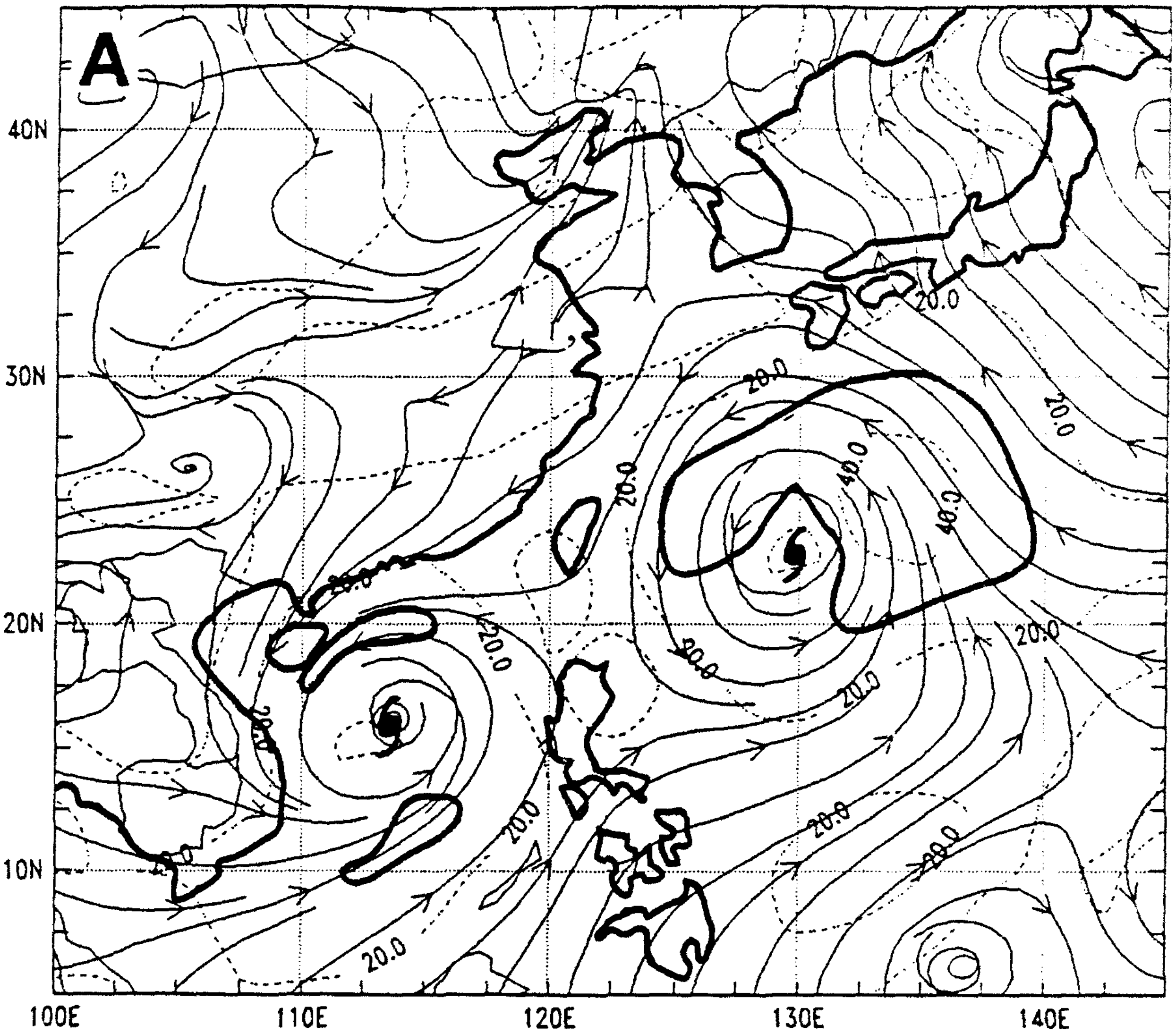


FIG. 5. Streamline and isotachs (kt) of the (a) analyzed and (b) 72-h forecast of the 925-mb flow from 1200 UTC 16 September 1990 NOGAPS run. The approximate positions of cyclones 19W (14°S. China Sea) and 20W (east of Taiwan) are indicated by the hurricane symbol. The isotach contour interval is 10 kt (~ 5 m s^{-1}) and the 30 kt (~ 15 m s^{-1}) isotach is highlighted as a measure of circulation extent.

problem is best illustrated by considering how JTWC prepares the synoptic-time warnings (0000 and 1200 UTC). The warning must be received by the users by +2.5 h (e.g., 0230 UTC), which means that the official forecast track must be completed by +1.5 h (e.g., 0130 UTC). The aids request is sent to FNOC at −1.5 h (e.g., 2230 UTC) with an extrapolated position valid at +0 h (e.g., 0000 UTC). However, the +0 h NOGAPS fields that should drive the OTCM (and the other forecast aids) are not available because the NOGAPS integration does not start until approximately +2.5 h (e.g., 0230 UTC). The lack of time synchronization between the warning, the guidance, and the initial positions, we employed a postprocessing procedure that for initial conditions (e.g., a 12-h forecast from the 1200 UTC NOGAPS run valid at 0000 UTC) and for the time-dependent lateral boundary conditions for the OTCM. Thus, we might expect that the quality of the synoptic-time OTCM forecasts would be poorer than those from the off-time (0600 and 1800 UTC) runs, which would benefit from "newer" NOGAPS field data (the NOGAPS analysis and +06-h forecast is completed at approximately +3.0 h for use as initial conditions). More importantly, the NOGAPS track forecast would not be available until +4.5 h, about the time JTWC is preparing the off-time warning (e.g., 0600 UTC). Given the lack of coincidence in time between the warning, the guidance, and the initial positions, we employed a postprocessing procedure that eliminates initial position differences between the NOGAPS track and the operational forecasts of the aids and that provides more realistic guidance to the

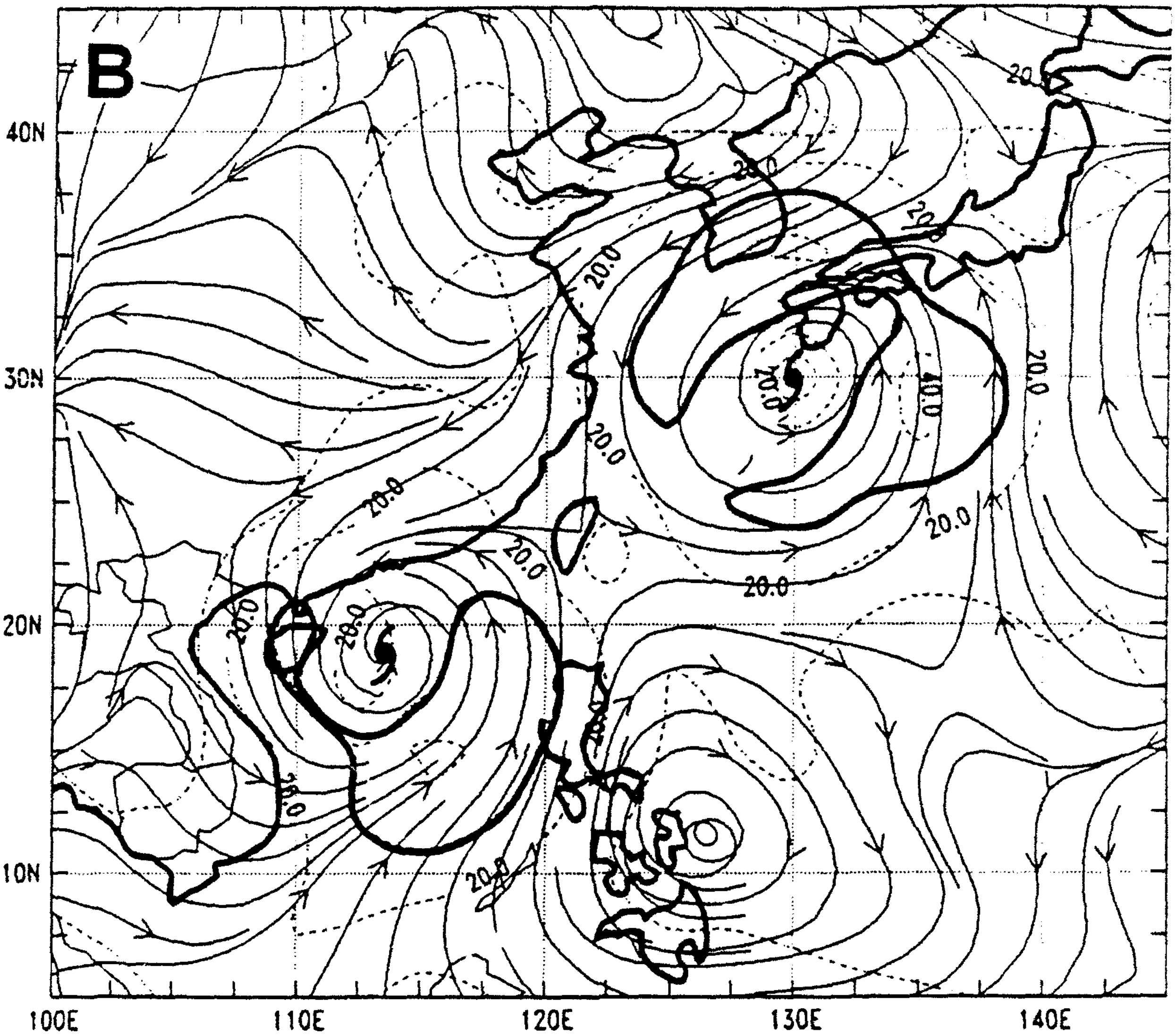


FIG. 5. (*Continued*)

forecaster by accounting for the time when the warning is issued. The postprocessing procedure is a two-step process.

In the first step, the raw NOGAPS track is decomposed into three 24-h motion vectors from the positions at $t = 0$, 24, 48, and 72 h (when available). The track is then reconstructed from the initial position given in the JTWC aids request message using rhumb lines and the motion vectors. This process aligns the NOGAPS track with the tracks from the other aids. Additionally, the realignment assumes that the most valuable component of the forecast is the motion vice the positions because of uncertainties associated with the initial location in the model solutions.

The second step biases the motion-derived forecast track toward persistence following a technique developed by Allen (1984). This modification reduces unrealistic (i.e., nonpersistent) motion in the short-term (0–36-h) forecast track. Figure 8 illustrates the "persistence-correction" procedure. A rhumb line is drawn from the initial position to the 72-h forecast (or earlier, if the 72-h position is not available) and the line is divided into 24-h segments. This is the "long-term" component of the track. A 24-h extrapolation is then made using the motion from the 0- and the 12-h observed positions (persistence), and the 24-h persistence-corrected forecast is simply the midpoint between the long-term track and the extrapolation. The process is repeated for the 48-h forecast, except that the persistence extrapolation is based on the 0–24-h persistence-corrected forecast. The choice of weighting between the persistent and the long-term track is not optimal in a statistical sense and alternative weightings may yield even better short-range error statistics.

The efficacy of the postprocessing is illustrated in Fig. 9, where we compare the raw and postprocessed forecasts on a one-for-one or homogeneous basis. The addition of persistence greatly improves the 24-h mean

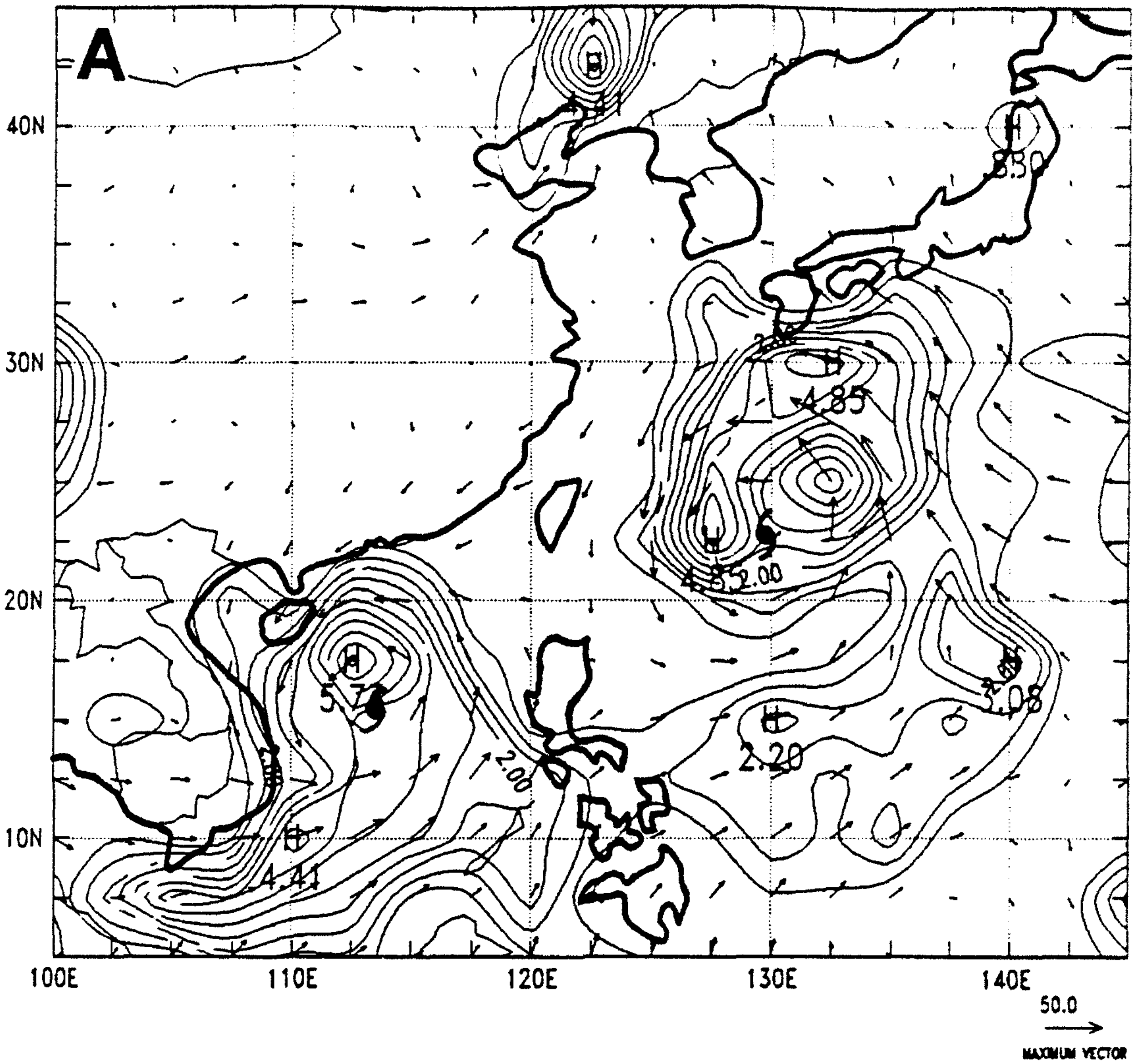


FIG. 6. Rainfall rate (cm d^{-1}) and 925-mb flow vectors at (a) t = 12 h (accumulated from 0 to 12 h) and (b) 72 h (accumulated from 60–72 h) from the 1200 UTC 16 September 1990 NOGAPS run. The approximate positions of cyclones 19W (South China Sea) and 20W (east of Taiwan) are indicated by the hurricane symbol. The contour interval is 0.5 cm d^{-1}.

forecast error (24%) while making modest improvement in the 48- (9%) and 72-h (5%) mean errors. The small reduction in the 72-h error is a consequence only of reducing the initial position error and demonstrates how large position errors at the initial time (151 km) are lost in the much larger uncertainty at 72 h (585 km) to yield much smaller changes (28 km).

An additional test of the NOGAPS track postprocessing was made by applying the procedure to the OTCM forecasts. The purpose was first, to ensure a fair comparison of the two dynamical models (i.e., both following the same rules), and second, to contrast two approaches to persistence correction. The OTCM employs a dynamical preprocessing procedure in which the initial wind fields in the vicinity of the cyclone are modified to steer the vortex along the initial motion vector (Shewchuk and Elsberry 1978). By contrast, the persistence biasing (Allen 1984) used in the NOGAPS postprocessing (see Fig. 8) takes a geometric approach and requires only the 72-h forecast position and the initial position and motion. The mean forecast errors for both the pre- and postprocessed OTCM forecasts were virtually identical (+3- and −2-km differences at 24 and 48 h, respectively). Thus, the two approaches provide similar improvements and the following comparisons use the operational (dynamical persistence correction) OTCM tracks. We also note that the geographic location of the OTCM grid is de-

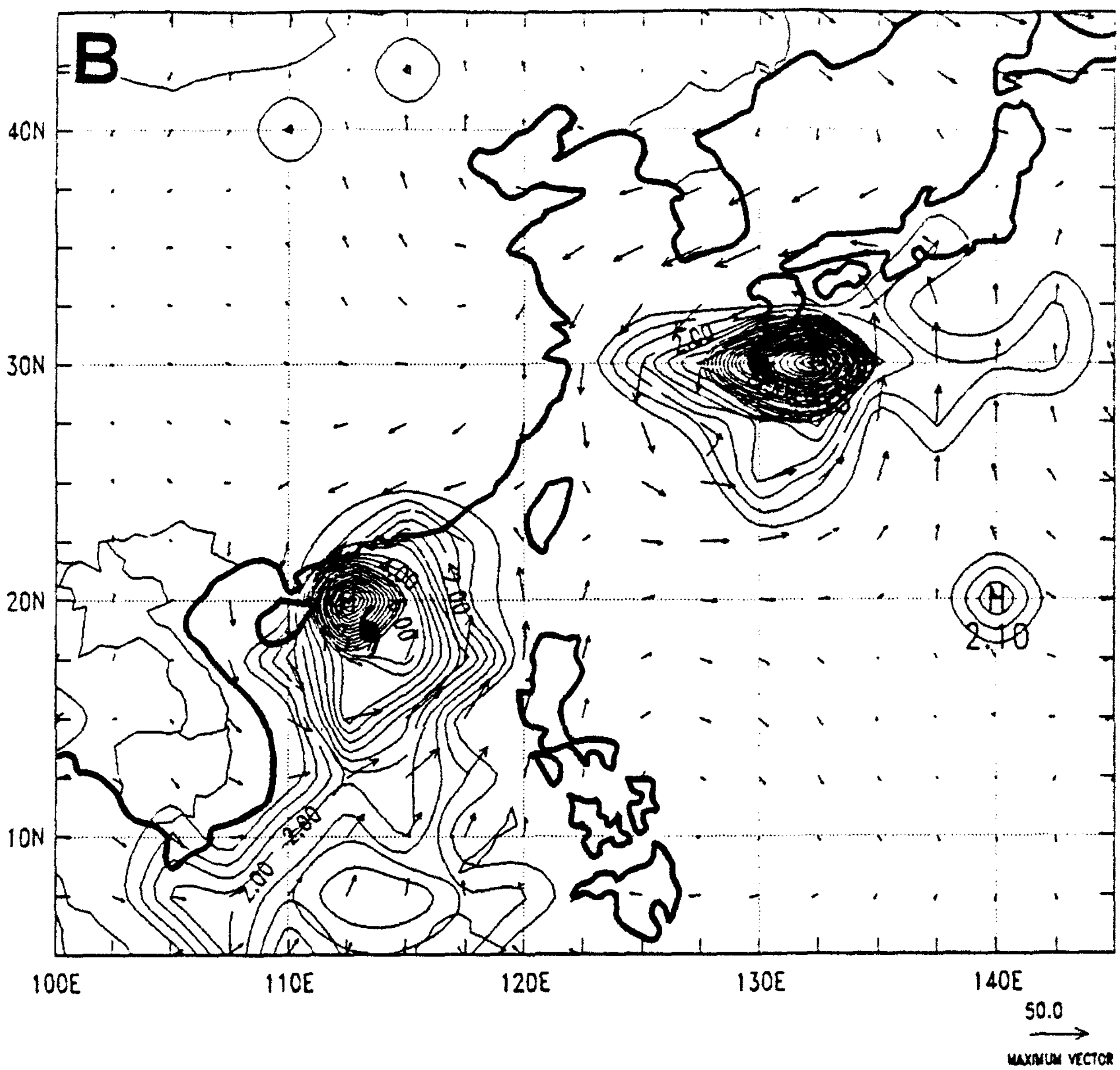


FIG. 6. (*Continued*)

fined by the JTWC operational initial position so that all forecast tracks in fact start from the same point.

e. Operational evaluation of the track forecasts

The NOGAPS track forecasts were extracted from the 0000 and 1200 UTC synoptic-time solutions and then postprocessed tracks were generated from the synoptic (+00 h) and "off-time" (+06 h) JTWC aid request data. For example, the 0600 (1800) UTC off-time adjusted NOGAPS track would be constructed using the earlier 0000 (1200) UTC NOGAPS raw motion vectors and the 0600 (1800) UTC JTWC aids request position and observed initial motion data.

To concentrate on operational utility, we restricted the comparison of the NOGAPS tracks to the +06-h postprocessed NOGAPS forecast and the off-time runs of OTCM and CLIP, all valid at the same times. These forecasts 1) use the same vortex parameters; 2) would be available to JTWC at the same time; and 3) use the most recent NOGAPS fields. In essence, we penalize NOGAPS by projecting the track from a future position (+06 h) in a similar way that the OTCM is handicapped by using 12-h-old forecasts vice analysis/6-h forecast fields for initial conditions.

Figure 10 gives the 72-h mean forecast errors stratified by synoptic (0000 and 1200 UTC) versus off-time (0600 and 1800 UTC) forecasts. The comparison is

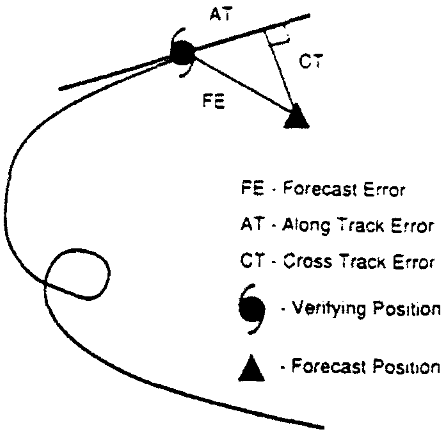


FIG. 7. Definition of the track errors: FE—forecast error; XT—cross-track error; AT—along-track error.

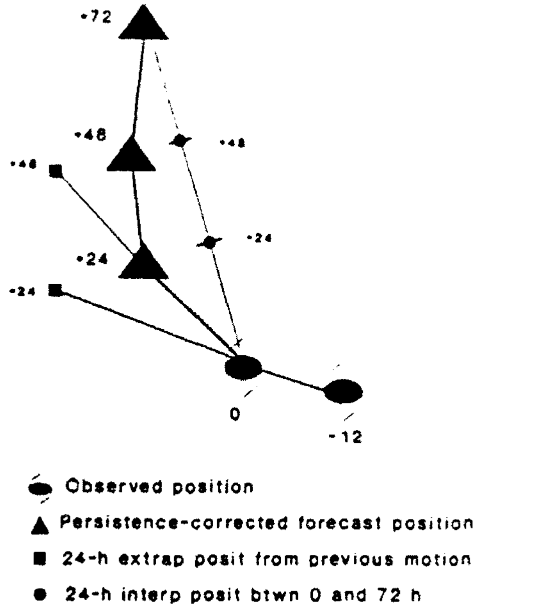


FIG. 8. The persistence-correction procedure used to bias the NOGAPS track toward the initial observed motion. See text for a description of the method.

nonhomogeneous to show how the performance of each aid changes separately. First note the small difference between the CLIP forecasts from 0000/1200 UTC and the 0600/1800 UTC runs (−1.3%). This is the expected result as the input to the CLIP model is independent of the NOGAPS fields. By contrast, the OTCM is somewhat better at the off times (−2.7%) and NOGAPS worse (+5.3%). The slight OTCM improvement is likely due to the availability of newer fields, and the NOGAPS degradation a consequence of extrapolating the forecast in time. Although traditional tests of statistical significance would fail to prove the forecasts are "different," the larger magnitude of the change, vis-à-vis CLIP, and the sense of the change fit our expectations. Furthermore, restricting the model evaluation to the off times compares the "best" OTCM forecasts to the "worst" NOGAPS forecasts.

A homogeneous comparison of the mean forecast error between NOGAPS, CLIP, and OTCM is given in Fig. 11. We first note that the CLIP errors at 72 h are about 10% lower than in previous years (Tsui and Miller 1988). Thus, the sample may not be fully representative of the track types that commonly occur in the western North Pacific, as discussed in section 4a. One reason for the low CLIP (and OTCM) errors was the lack of storms with unusual motion, such as loopers and stallers. Obviously, better guidance is needed for these anomalous cases and they will present a difficult challenge to the global model. Despite somewhat poorer NOGAPS performance at 72 h relative to CLIP, the NOGAPS track postprocessing yielded slightly better errors at 24 and 48 h. The OTCM was somewhat better than NOGAPS at 24 and 72 h, but the difference was at most 4%. Furthermore, NOGAPS was second only to the OTCM and had lower errors than the other aids (not shown). Therefore, the model is a viable candidate for further testing and operational use. This per-

TABLE 2. NOGAPS initial position error as a function of cyclone category.

Cyclone intensity category (defined according to JTWC operating instructions)	Number of cases	Initial position error (km)
Tropical depression (<34 kt or ~18 ms^{-1})	49	204
Tropical storm (≥34 kt or ~18 m s^{-1} and <64 kt or ~33 m s^{-1})	90	154
Typhoon (≥64 kt or ~33 m s^{-1})	147	141
Super typhoon (≥130 kt or ~67 m s^{-1})	11	115
All categories	287	55

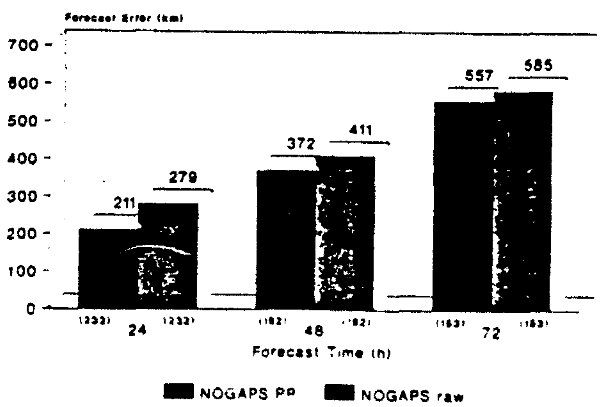


FIG. 9. Homogeneous comparison of the mean forecast errors (km) at t = 24, 48, and 72 h for the raw and postprocessed NOGAPS track forecasts. The number of cases is given in parentheses below the error bar and the value of the error is given above the bar.

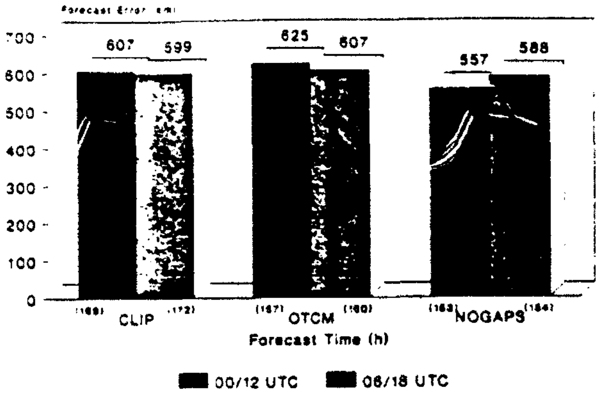


FIG. 10. 72-h mean forecast error (km) of CLIP, OTCM, and NOGAPS for the synoptic (00/12 UTC) and off-time (06/18 UTC) forecasts. The number of cases is given in parentheses below the error bar and the value of the error is given above the bar.

formance is particularly noteworthy given the intermittent application of the NOGAPS TC analysis methodology.

Statements concerning better or worse must at least consider statistical significance. Traditional significance tests (e.g., Student's t) would show that the models are statistically similar with regard to mean forecast error. While we cannot claim the statistical superiority of any one forecast model, we argue that statistical significance of the mean forecast error should not be overly emphasized when evaluating the *potential* operational utility of an aid for two reasons.

First, these tests typically assume that the cases are drawn from a normally distributed population and that the samples are independent, that is, the errors from one forecast to the next are not correlated. While forecast errors are not normally distributed in a strict sense, the more serious difficulty in evaluating statistical significance is the independence issue. Jarrell et al. (1978) showed that a separation of 36-h between cases within a storm would reduce serial correlation to near zero, as estimated from the autocorrelation function. Alternatively, all cases could be used, but an effective degrees of freedom (number of independent cases) could be estimated from the sample (e.g., Keenan and Fiorino 1987) when calculating the test parameter. Both approaches to reducing serial dependence have the effect of requiring many years of cases to establish that one aid is statistically superior to another, especially when the differences in mean errors are small (~5%) and the standard deviations are large (typically ~60% of the mean). Thus, in practice it is virtually impossible to collect a large set of independent cases when an aid is developed and/or runs in an evolving operational environment. The stringent case requirement agrees with operational experience that several years of operational use are needed for the forecasters to accept an aid. Furthermore, a small (~5%) statistically significant difference may not necessarily be significant operationally as few "bad" aids have been eliminated from JTWC run list (14+ in 1990) based on statistical analyses alone. Rather than claiming that NOGAPS is or will be the best, we are simply encouraged with the model's first-year performance. Only refinement in the TC analysis procedure and more experience will establish the true operational skill of the NOGAPS TC track forecast.

A second reason for not stressing statistical significance is that mean forecast error is only a gross measure of forecast characteristics, as discussed earlier. Biases and performance under different synoptic conditions may have greater relevance to the operational forecaster and should be addressed by the modelers when developing the TC analysis procedure.

f. Track biases and stratifications

Median AT and CT errors, used as measures of speed and track biases, are shown in Figs. 12 and 13. The two dynamical models have a large "behind the track" (negative median AT error) or slow bias, whereas CLIP has a much smaller slow bias. The magnitude of the AT errors (i.e., mean of the absolute value of AT error)

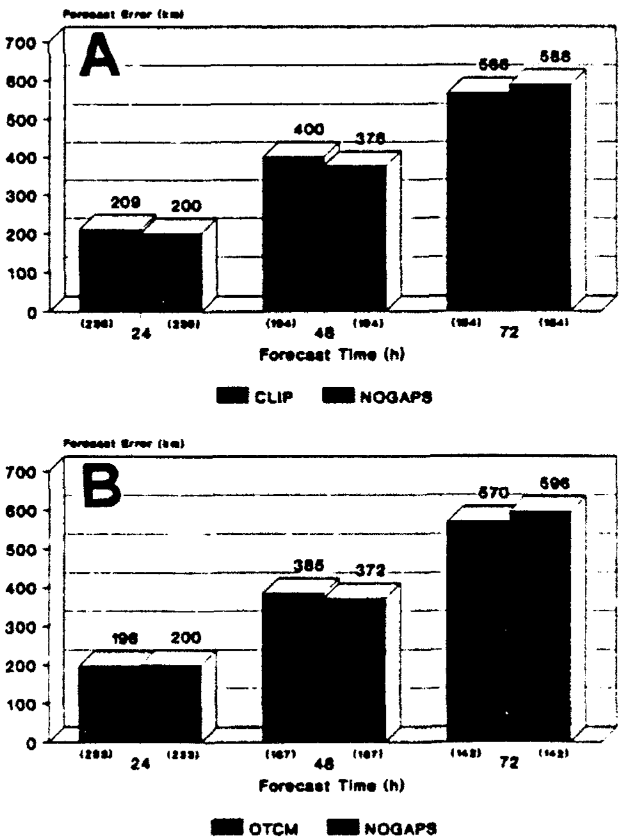


FIG. 11. Homogeneous comparison of the mean forecast errors (km) for (a) CLIP and NOGAPS and (b) OTCM and NOGAPS at t = 24, 48, and 72 h. The number of cases is given in parentheses below the error bar and the value of the error is given above the bar.

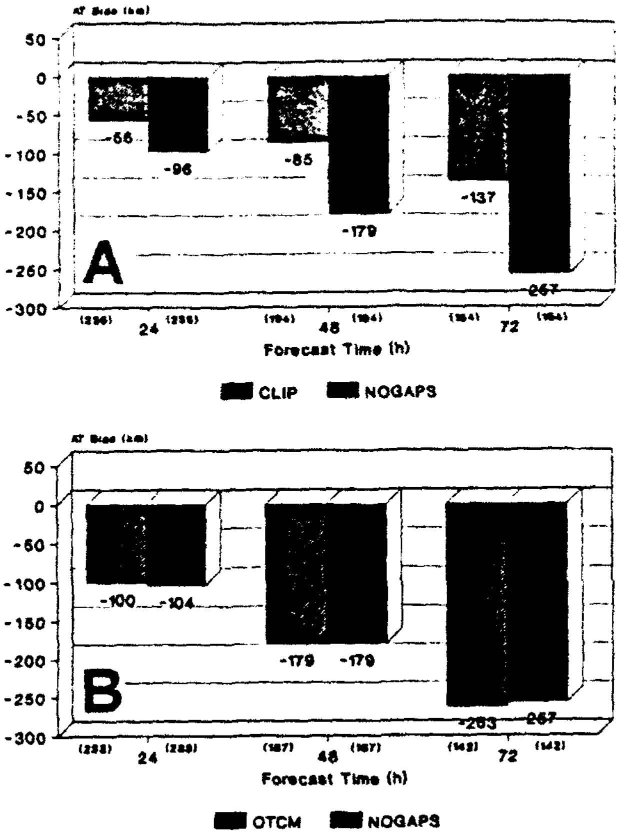


FIG. 12. Same as Fig. 11 except for the median along-track error (speed bias).

were very similar (not shown) so that differences in the AT biases were related to speed. However, the smaller CLIP AT bias at 72 h was compensated by a much larger right-of-track bias (Fig. 13a) than in either OTCM or NOGAPS. Williams (1986) found that CLIP had little AT bias so that the large 72-h AT bias in this sample may be yet another indication that the tracks were not very typical and that our results may not translate well to future seasons. More notably, the NOGAPS CT bias is smaller than that of the OTCM, which is important given comparable AT error characteristics. This result is somewhat surprising given the unrealistically large horizontal extent of the vortex in NOGAPS, as discussed in section 4b, and should be addressed in future evaluations. We should also point out that decomposing the forecast error into east–west, north–south (i.e., a geographic frame of reference) components would have aided the interpretation of the AT/CT biases. Unfortunately, the JTWC error analysis program we used to calculate the statistics did not have this capability.

To understand how model forecast error and biases depend on synoptic conditions, we stratified the forecasts according to track type, that is, straight runner, recurver, and north (and anomalous) runners. Obviously, these results have limited applicability to forecasting unless the track type could be predicted reliably. However, these statistics at least give a sense of how the guidance varies under different flow regimes, given a relationship between track type and synoptic flow (see Harr and Elsberry 1991). We concentrated on the 72-h forecasts as they are the most important in establishing the forecast track scenario (Guard et al. 1992) and showed the greatest differences in overall biases. The stratified mean forecast error is given in Fig. 14. Whereas the mean errors for all cyclones are similar for all the aids, they are not distributed uniformly with track type. NOGAPS made its best forecasts on straight runners and poorest forecasts for recurvers. By contrast, CLIP and OTCM showed more consistent performance. However, most of the relatively large NOGAPS recurvature error was due to the model's failure to recurve cyclones 21W and 22W. This failure resulted in very large 72-h mean forecast errors of 1310 and 967 km for 21W and 22W, respectively. Removal of these cases from the dataset would substantially improve the statistics in NOGAPS favor. However, the main point is that NOGAPS showed good skill for straight runners and that cyclones 21W and 22W would be good cases for future testing of the NOGAPS TC analysis proce-

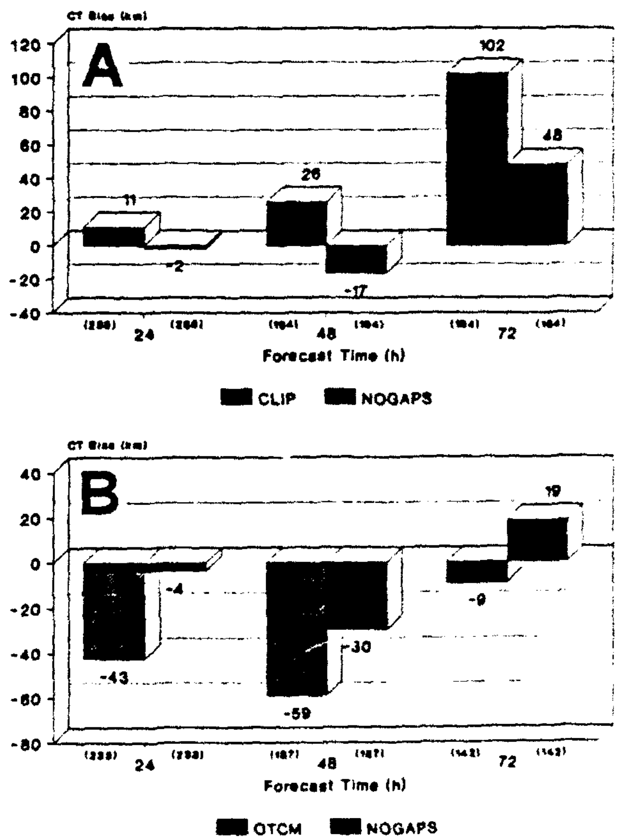
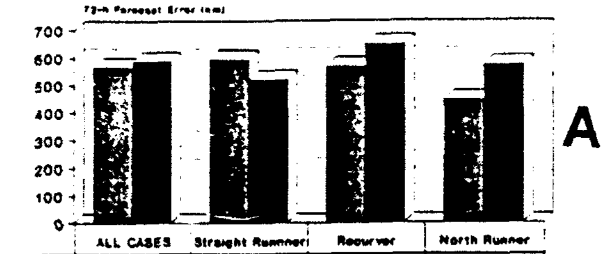
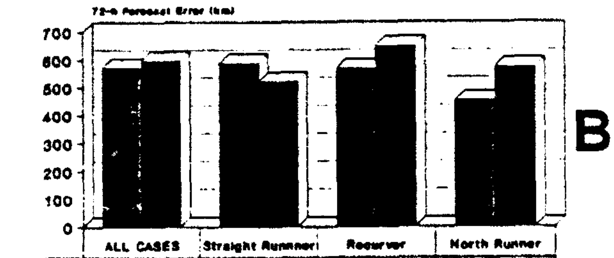


FIG. 13. Same as Fig. 11 except for the median cross-track error (track bias).



	ALL CASES	Straight Runner	Recurver	North Runner
CLIP	566	594	567	444
NOGAPS	588	520	648	572
# cases	154	62	76	16

CLIP NOGAPS



	ALL CASES	Straight Runner	Recurver	North Runner
OTCM	570	586	567	461
NOGAPS	596	620	648	572
# cases	142	56	70	16

OTCM NOGAPS

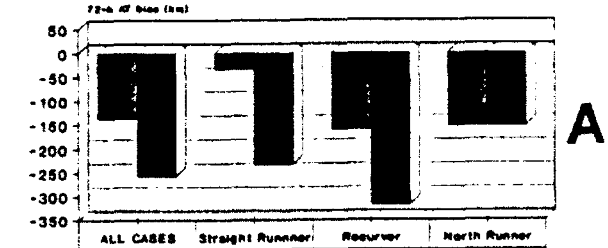
FIG. 14. Homogeneous comparison of the 72-h mean forecast errors (km) for (a) CLIP and NOGAPS and (b) OTCM and NOGAPS stratified by track type.

dure and may indicate the potential for catastrophic recurvature failures.

The AT and CT biases stratified by track type are presented in Figs. 15 and 16. The speed biases for the north-running cyclones were smaller than for the other track types for all models. However, the track biases were much larger and to the left (negative CT error) of the verifying track, that is, the models tended toward a climatological northwest track rather than moving north. Although CLIP had a very small AT bias for straight runners, the model was biased right of track, which is again indicative of a bias toward a climatological northwest track. Similar, but more exaggerated, biases were found for OTCM in straight-runner situations, whereas NOGAPS had the lowest CT bias as a consequence of correct predictions of equatorward turns for cyclones 16W and 30W. Given the large and left-of-track errors in the NOGAPS forecasts for recurvers 21W and 22W, the small CT bias must have resulted from a right-of-track bias for the other recurving cyclones. The one-way influence tropical model was more consistently left of track, which suggests that the OTCM may have been late in predicting the point of recurvature, whereas NOGAPS may have been early.

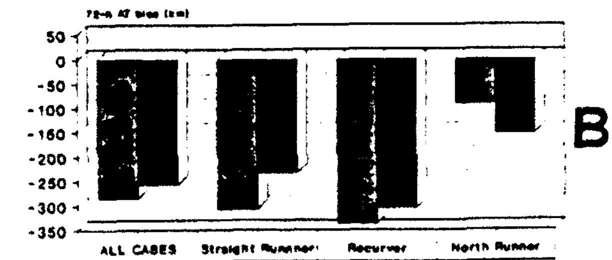
The TC analysis procedure was applied intermittently during the first year of testing due to the inevitable problems associated with bringing a new operational procedure on-line, particularly one that requires coordinated communication over long distances. While many of the deficiencies have since been worked out, over half of the verifying 72-h NOGAPS forecasts in this evaluation were started from initial conditions in which no synthetic TC observations were applied. That is, the cyclone vortex in the initial conditions was analyzed from a forecast field (the first guess) and existing observations alone without the benefit of the synthetic TC soundings.

To determine how NOGAPS skill was impacted by the insertions of synthetic TC observations, we stratified the 72-h forecasts for cases with and without application of the procedure. We also wanted to detect possible interactions of the TC analysis with other aids, such as the OTCM, which rely on NOGAPS for initial conditions and forecasted large-scale flow at the lateral boundaries. The mean forecast errors for this stratification are given in Fig. 17. The CLIP forecasts were somewhat worse when the TC analysis was applied because most of the missing cases occurred in the beginning of the cyclone when the positions were less accurate. CLIP is known to have somewhat lower forecast errors for stronger cyclones (Tsui and Miller 1988). Perhaps the slightly lower NOGAPS errors with the



	ALL CASES	Straight Runner	Recurver	North Runner
CLIP	-137	-33	-159	-152
NOGAPS	-257	-233	-318	-153
# cases	154	62	76	16

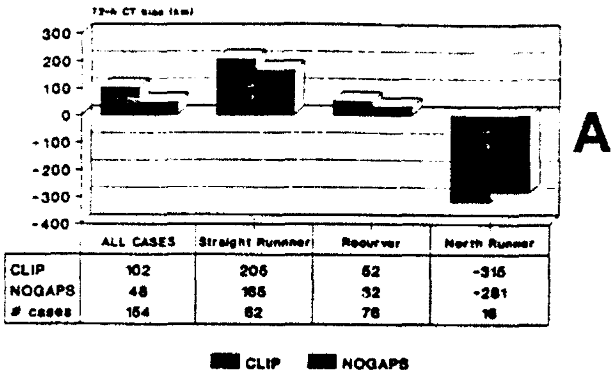
CLIP NOGAPS



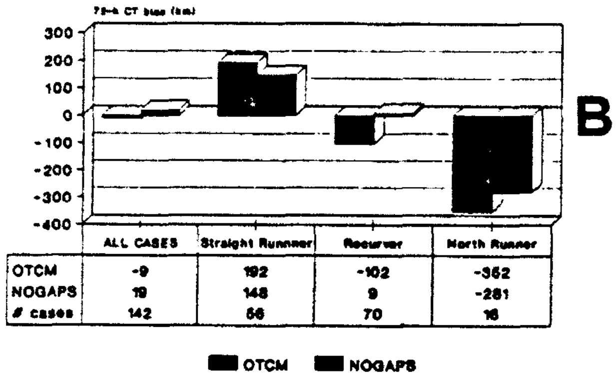
	ALL CASES	Straight Runner	Recurver	North Runner
OTCM	-286	-307	-337	-91
NGPS	-257	-233	-306	-153
# cases	142	56	70	16

OTCM NGPS

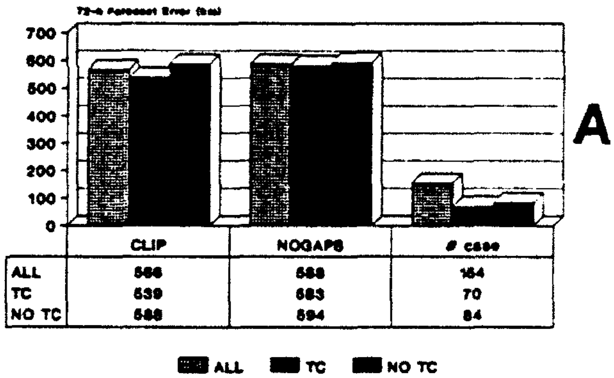
FIG. 15. Same as Fig. 14 except for median along-track error (speed bias).



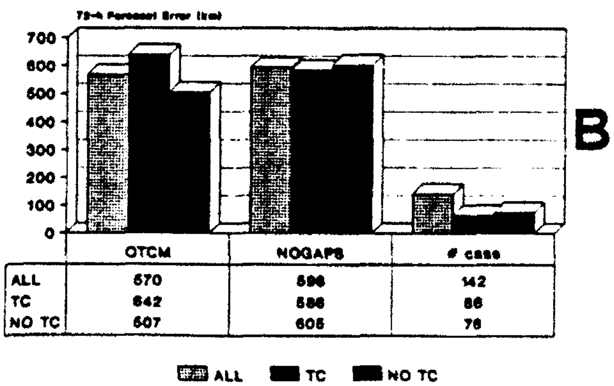
	ALL CASES	Straight Runner	Recurver	North Runner
CLIP	102	206	62	-316
NOGAPS	46	165	32	-281
# cases	154	62	76	16



	ALL CASES	Straight Runner	Recurver	North Runner
OTCM	-9	192	-102	-362
NOGAPS	19	148	9	-281
# cases	142	66	70	16



	CLIP	NOGAPS	# case
ALL	566	588	154
TC	539	583	70
NO TC	588	594	84



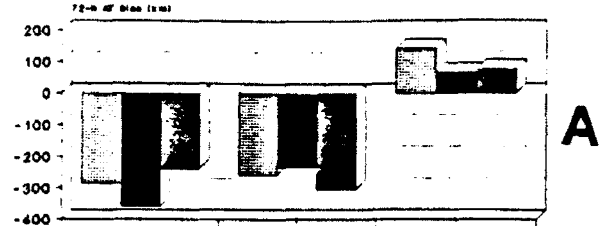
	OTCM	NOGAPS	# case
ALL	570	596	142
TC	642	586	66
NO TC	507	605	76

FIG. 17. Homogeneous comparison of the 72-h mean forecast errors (km) for (a) CLIP and NOGAPS and (b) OTCM and NOGAPS stratified by whether the NOGAPS TC synthetic observations are used.

TC analysis were also related to the intensity difference, but otherwise there was little change in the NOGAPS forecasts. However, the OTCM forecasts were seriously degraded (over 20%) when the NOGAPS TC analysis procedure was employed (Fig. 17b). This finding is especially noteworthy because the large errors occurred precisely when the OTCM should have performed better, as Tsui and Miller (1988) found that OTCM skill varies even more strongly with intensity and is better for stronger TCs. The deleterious effect of the NOGAPS TC analysis on the OTCM was examined in terms of AT and CT bias (Fig. 18a). The largest effect was in the speed bias, with a larger negative AT bias with the synthetic observations; that is, the OTCM storm moves even more slowly. One explanation is that the large extent of the analyzed TC vortex distorted and weakened the large-scale steering flow used in the OTCM initial conditions. Even though this steering flow is derived from spectrally truncated fields, a large vortex could still leave behind a weak remnant (Fiorino and Elsberry 1989b).

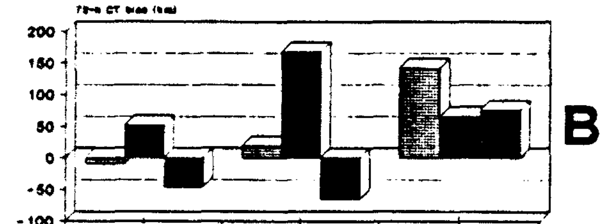
The harmful interaction of the OTCM with the global model TC analysis should be considered when employing global model fields in ancillary TC track models. The underlying assumption of most TC track models is that the large-scale forcing fields represent a steering flow. This assumption will clearly be violated in the era of global model TC forecasting. Still, the OTCM deterioration is somewhat puzzling given that the NOGAPS vortex did not appear to change drastically when the synthetic observations were not inserted. The changes in the vortex must have been more subtle, which suggests a finer sensitivity than might have been expected initially. Additionally, we cannot conclude that the NOGAPS TC analysis caused the change in OTCM forecast skill or that the TC analysis methodology is somehow flawed. Rather, the impact may have been due solely to the inconsistent application of the TC analysis.

Whereas the NOGAPS mean forecast error changed little with TC analysis, the CT bias showed a much stronger signal (Fig. 18b) with a large rightward (generally poleward in the Northern Hemisphere) bias and a smaller leftward bias without the insertion. Although further study is needed, we speculate that this signature fits the expectation of a poleward drift from barotropic model results, given that the NOGAPS vortex appears to be unrealistically large. Analysis of the vortex in terms of symmetric and asymmetric components (Fiorino and Elsberry 1989a) may be useful in understanding how the synthetic TC observations change the vortex structure and the motion dynamics.



	OTCM	NOGAPS	# case
ALL	-285	-257	142
TC	-359	-233	66
NO TC	-239	-305	76

ALL TC NO TC



	OTCM	NOGAPS	# case
ALL	-9	19	142
TC	52	168	66
NO TC	-46	-65	76

ALL TC NO TC

FIG. 18. Homogeneous comparison of the (a) 72-h median along-track error (km) and (b) 72-h median cross-track error (km) for OTCM and NOGAPS stratified by whether the NOGAPS TC synthetic observations are used.

Finally, we examined the individual tracks in some detail. Besides confirming results from the statistics, this analysis revealed that the NOGAPS vortex slowed down and moved erratically at landfall, particularly over Southeast Asia. An example of this defect is given in Fig. 19, which shows the OTCM and NOGAPS forecasts for cyclone 19W. The storm ran straight, then dipped equatorward as it passed the island of Luzon in the Philippines, and then resumed a due westward course before making landfall on Vietnam. The NOGAPS vortex stalls and then bends northward before landfall, whereas the OTCM takes the storm over land. This difference suggests that the physical effects associated with land–sea contrasts and topography, which are accounted for in NOGAPS but are absent in the OTCM, are influencing the vortex motion (see Figs. 5b and 6b) and that the NOGAPS track forecast may require special treatment at landfall until model resolution is improved. Despite the poor track forecasts of NOGAPS in the vicinity of Vietnam, the global model did correctly predict the unusual equatorward turn toward to the south-southwest. This typifies some of the positive (e.g., good skill for straight runners) and negative aspects of the NOGAPS forecasts. Perhaps limited-area, high-resolution models will have a role in shorter-range forecasts near landfall as current global models lack sufficient resolution to realistically simulate the influences of physical processes on the tropical cyclone when these processes operate on scales that depend on finescale topography and land–sea contrasts.

5. Summary and discussion

We have performed a comprehensive evaluation of the tropical cyclone forecast skill of the Navy Operational Global Atmospheric Prediction System (NOGAPS) in the western North Pacific during the first year of operational testing of a procedure that improves the initial specification of tropical cyclones in the global model. The NOGAPS TC analysis procedure first creates a set of synthetic vertical TC wind profiles defined as the combination of a large-scale steering flow and an isolated TC vortex whose structure is derived from the observed storm location, maximum wind speed, and the radius of 30-kt (~ 15 m s^{-1}) winds. In 1990, the synthetic TC observations were added to the observational database used in the "posttime" run of the NOGAPS analysis (+9 h after synoptic time) because of operational constraints at FNOC. The posttime analysis improves the analyses/forecasts of the data assimilation cycle by including observations that did not reach FNOC in time for the "real-time" analysis (+2.5 h after synoptic time) used to initialize the global model forecast integration. Since 1990, the operational limitations have been eliminated and synthetic TC soundings are now used during both the real-time and posttime analyses. However, during the period considered in this study, the synthetic observations did not directly influence the global model forecasts. Rather, the initial TC vortex in the global model forecast integration came from the data assimilation analysis/forecast cycle. One consequence of the posttime analysis approach was that the initial position of global model TC was poor. Furthermore, the global model guidance was not available at the same time as the other aids used by the typhoon forecasters at JTWC. Thus, a postprocessing procedure was required to compensate for the initial position discrepancies and to align the NOGAPS track with that of the other aids for a fairer, and operationally more meaningful, comparison.

A unique aspect of our study was an examination of the relationship between low-level cyclone circulation activity, in the NOGAPS analyses and verifying forecasts, and TC formation. The analysis showed that NOGAPS was surprisingly accurate in anticipating TC genesis. We attributed the success to the quality of the large-scale analysis procedure in the tropics and to the parameterization of cumulus convection in the global model as the association occurred prior to the introduction of the synthetic TC observations.

The low- and midlevel structure of the NOGAPS cyclones was vertically stacked and reasonable in a first-

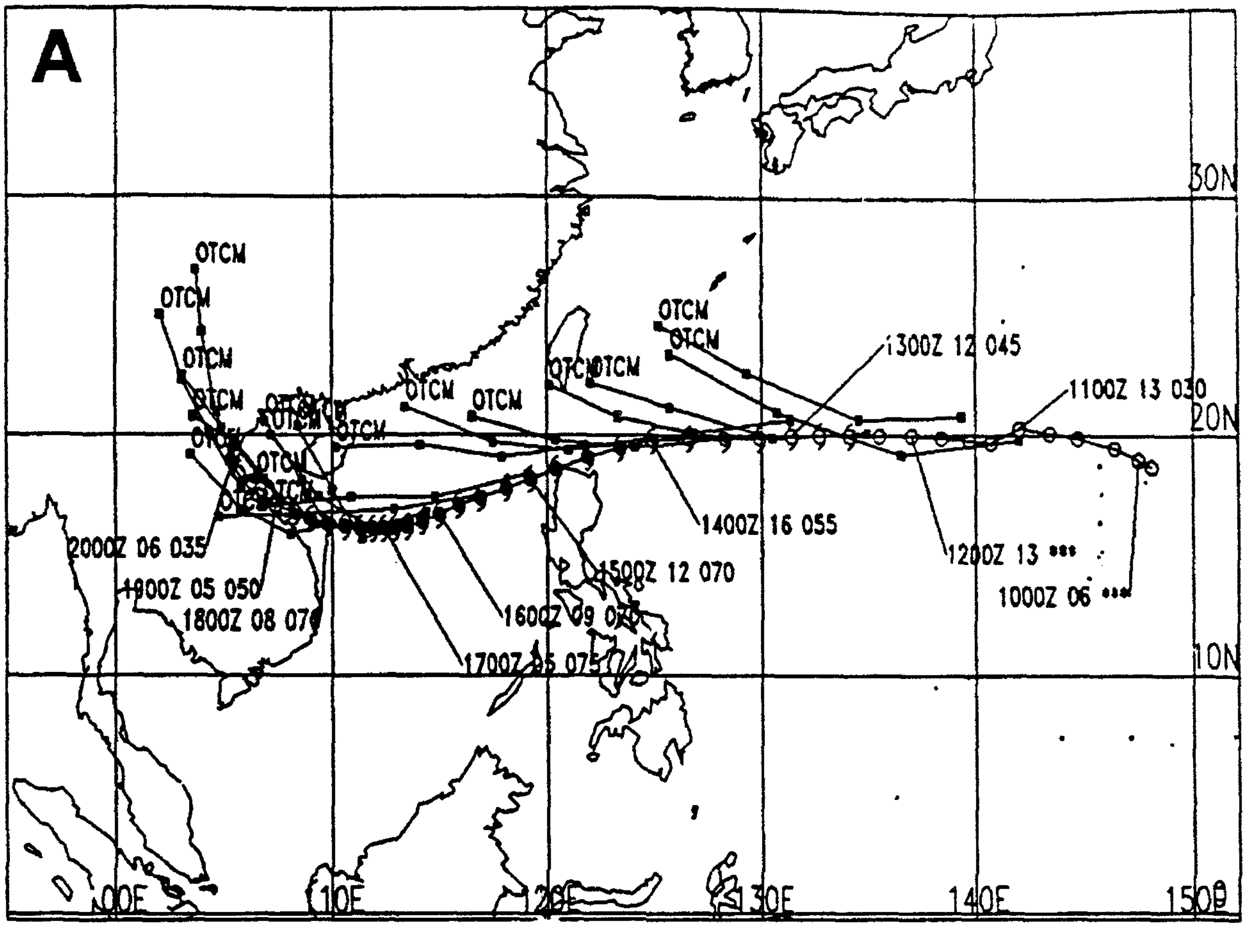


FIG. 19. The (a) OTCM and (b) NOGAPS track forecasts (every 12 h) for cyclone 19W, 10–20 September 1990. Working best-track positions are plotted every 6 h with circles (tropical depression), open hurricane symbol (tropical storm), and filled hurricane symbol (typhoon). The squares give the model forecast positions every 24 h. The working best-track positions are labeled with DDHH SP VVV, where DD is the day number, HH is the UTC time, SP is the working best-track speed of motion during the preceding 12 h, and VVV is the intensity in kt.

order sense, but the radius of 30-kt (15 m s^{-1}) winds was too large and the upper-level flow seldom contained anticyclonic outflow over the storm center. Precipitation rates were similar to those from TC composites (Frank 1977).

Despite these structural weaknesses, the mean track forecast error was comparable to the no-skill climatology/persistence aid and the best dynamical model, and revealed relatively little bias with regard to cross-track and along-track errors. Furthermore, the global model successfully predicted unusual, equatorward-turning tracks for several TCs. However, the NOGAPS forecast tracks at landfall showed abrupt changes in course and rapid deceleration; both features are likely related to the coarse horizontal resolution of the coastline in the global model. We also stratified track errors by track type and whether synthetic TC observations were included in the posttime analysis. The most significant finding was that the forecasts of the dynamical model OTCM, which uses NOGAPS for initial and lateral boundary conditions, were strongly and negatively influenced by the TC analysis in NOGAPS. This result implies that TC forecast aids that use synoptic-scale input from a global analysis/forecast system, and assume that the "synoptic" flow is free of tropical cyclone circulations, will have to be revised when TCs are routinely analyzed by global models.

Despite the 1990 operational limitations, we believe the first-year results in the western North Pacific are encouraging. This analysis, and the even better results from the 1991 season where synthetic TC observations were included in the real-time analysis (Goerss 1992), suggest that global models and data assimilation procedures have advanced to the point of producing operationally useful TC forecasts. Bengtsson et al. (1982), in the first comprehensive evaluation of the simulation of TC-like vortices in an operational global model, stated that they did not believe "models with a reso-

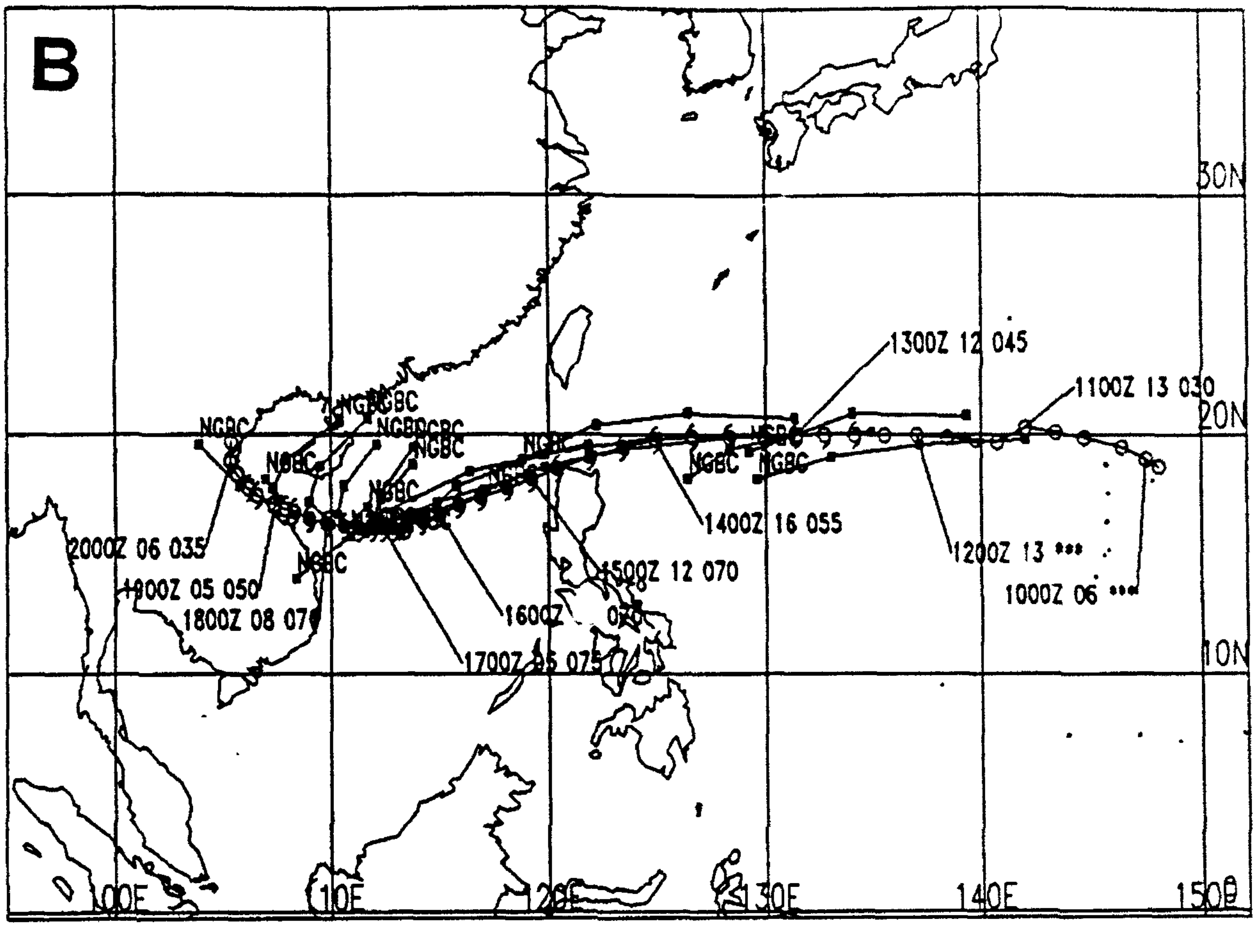


FIG. 19. (*Continued*)

lution of the ECMWF model [similar to NOGAPS circa 1990] should be used to predict tropical cyclones." The purpose of their study was to encourage modelers to develop procedures for analyzing TCs in their global models. Since the Bengtsson et al. (1982) paper, many operational centers have been actively pursuing the problem, as noted in the Introduction. However, Bengtsson et al. may have been too pessimistic regarding potential operational utility. The initial results from NOGAPS in the western North Pacific in 1990 imply that even coarse-resolution global models have potential TC forecast capabilities. As the spatial resolution of the global models inevitably improves, we expect that the global models will become invaluable tools in improving TC track prediction.

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