Performance of Global and Regional NWP Models in Their Prediction of Typhoon Nat (1991)

JOHNNY C. L. CHAN

Department of Physics and Materials Science, City University of Hong Kong, Kowloon, Hong Kong

(Manuscript received 11 January 1994, in final form 20 October 1994)

ABSTRACT

In 1991, Typhoon Nat over the western North Pacific made four directional reversals due to its interactions with two other tropical cyclones (TCs), Luke and Mireille. This paper analyzes the performance of three global and two regional models in predicting the movement of Nat to determine the extent to which each of the models was capable of correctly simulating such binary interactions. The global models include those of the European Centre for Medium-Range Weather Forecasts (ECMWF) and the U.K. Meteorological Office (UKMO) and the U.S. Navy Operational Global Atmospheric Prediction System (NOGAPS). The regional models studied are the Typhoon Model (TYM) of the Japan Meteorological Agency and the One-Way Tropical Cyclone Model (OTCM) of the U.S. Navy.

It was found that in general the global models made better predictions than the regional ones, especially when the large-scale flow was well defined. During the interaction periods, the UKMO model and the TYM were the best. The ECMWF model was also quite good in capturing the latter part of the Nat–Mireille interaction when Mireille had a large circulation. Although NOGAPS had a bogus vortex in the model, it did not predict the interactions very well. The OTCM was the worst of the models, possibly because of the steering flow imposed onto the model vortex.

The main conclusions from this study are that a bogus vortex representative of the actual TC appears to be necessary for properly simulating the interaction between TCs. An increase in resolution may also help in this respect. However, imposing a persistence vector into a model to simulate steering may prove detrimental in predicting binary interactions.

1. Introduction

In 1986, Typhoon Wayne over the western North Pacific (WNP) made four directional reversals during its lifetime and resulted in large forecast errors, as documented by Chan and Lam (1989). One of these four reversals was associated with its interaction with another tropical cyclone (TC). The global model of the European Centre for Medium-Range Weather Forecasts (ECMWF) failed badly during this period of mutual interaction.

During September 1991, another typhoon, Nat, also had four directional reversals (Fig. 1), three of which resulted from its interaction with two other TCs, Luke and Mireille. With such an unusual track, it would be of interest to see whether different operational NWP models (which may or may not have a bogus vortex) have different forecast accuracies and, if so, to determine the reasons for these differences. The model forecasts available include those from three global models—the ECMWF, the U.S. Navy Operational Global Atmospheric Prediction System (NOGAPS), and the U.K. Meteorological Office (UKMO)—and two regional models—the One-Way Tropical Cyclone Model (OTCM) of the U.S. Navy and the Typhoon Model (TYM) of the Japan Meteorological Agency (JMA). Since predictions from both global and regional models are available, comparisons between and among the two types are possible. The purpose of this study is therefore to determine whether the accuracy of the model depends on the existence of a bogus vortex, resolution, artificial boundary conditions, etc. A knowledge of such dependencies will help in the future improvements of the models. It must be pointed out that this study is not to compare model accuracies. The results should not be used as such, but rather as indicators for improving an individual model as well as determining the circumstances under which the model predictions may be used as guidance.

The synoptic situations associated with the different movements of Typhoon Nat, including its interaction with Tropical Storm Luke and Supertyphoon Mireille, are presented in section 2. The models to be studied are then briefly described in section 3. In past analyses of model predictions of TC movement, the climatology–persistence (CLIPER) predictions have generally been used as a benchmark for gauging the performance of a particular model since the latter are considered to

Corresponding author address: Dr. Johnny C. Chan, Department of Physics and Materials Science, City University of Hong Kong, Tat Chee Avenue, Kowloon, Hong Kong.

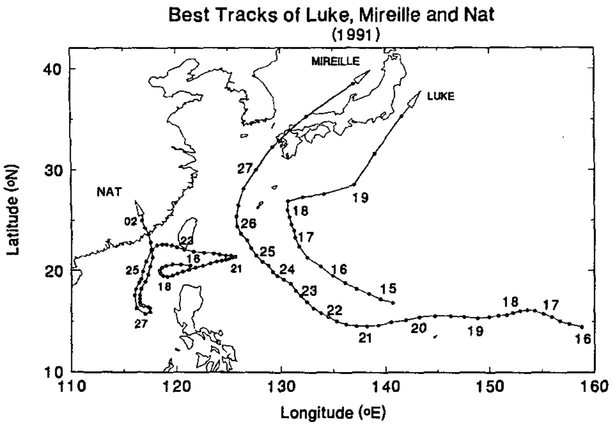


FIG. 1. Six hourly positions of the best tracks of Tropical Storm Luke, Supertyphoon Mireille, and Typhoon Nat. The numbers correspond to the 0000 UTC position on that day.

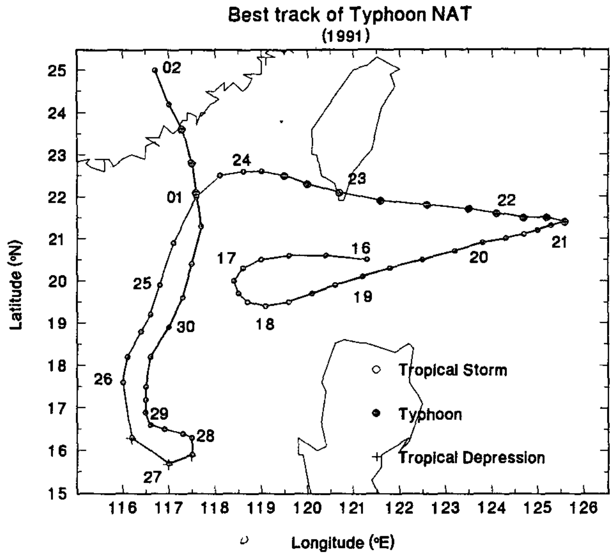


FIG. 2. Six hourly positions of the best track of Typhoon Nat. The numbers correspond to the 0000 UTC position on that day. Different symbols indicate the various intensities of Nat.

have no skill (Neumann and Pelissier 1981). However, because the CLIPER model is a statistical one and therefore incapable of predicting binary interactions, not much insight can be gained by comparing the NWP model predictions with those of CLIPER. (Such comparisons had actually been made, with the trivial and expected result that nearly all the NWP model predictions are better.) Forecast errors are also not very meaningful because in binary interaction situations, the forecast error can be small and yet the forecast direction of movement is completely wrong. Therefore, this study focuses only on the actual predicted tracks of Nat from individual models. These tracks are then compared with the best track to see whether each of the models is capable of predicting the direction reversals. These results are presented in section 4. A summary is then given in section 5 with a discussion on future improvements in the forecast accuracy.

2. The life history of Nat

Nat first developed in the monsoon trough over the Bashi Channel (between Taiwan and the Philippines) at 0600 UTC 15 September 1991. [Hereafter, all references to date/time will be in the format MMDDHH, where MM is the month (09 = September, 10 = October), DD the day of the month, and HH the hour in UTC. This particular time will therefore be referred to as 091506.] It initially interacted with Tropical Storm Luke and then with Supertyphoon Mireille after the demise of Luke. Therefore, it is convenient to discuss the track of Nat by dividing it into four periods: (a) Nat–Luke interaction period 091600–091806; (b) first no-interaction period 091812–092018; (c) Nat–Mireille interaction period 092100–092600; and (d) second no-interaction period 092606–100200. A detailed track of Nat is given in Fig. 2.

a. Nat–Luke interaction period (091600–091806)

Nat intensified to a tropical storm at 091606 with an intensity of 35 kt (17 m s^{-1}). At this time, another Tropical Storm Luke was almost due east of Nat (see Fig. 1). The two TCs began in interact with each other. Between 091606 and 091806, the positions of Nat relative to those of Luke show a cyclonic rotation with a rather constant separation distance of ~13° latitude (Fig. 3). During this interaction period, the binary sys-

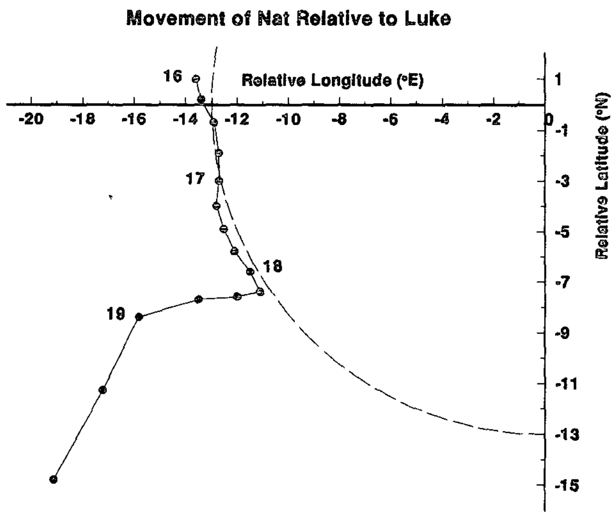


FIG. 3. Six hourly positions of Typhoon Nat relative to the corresponding positions of Tropical Storm Luke. The numbers along the relative track indicate the 0000 UTC position on that day. The dashed arc has a radius of 13° latitude centered on the position of Luke.

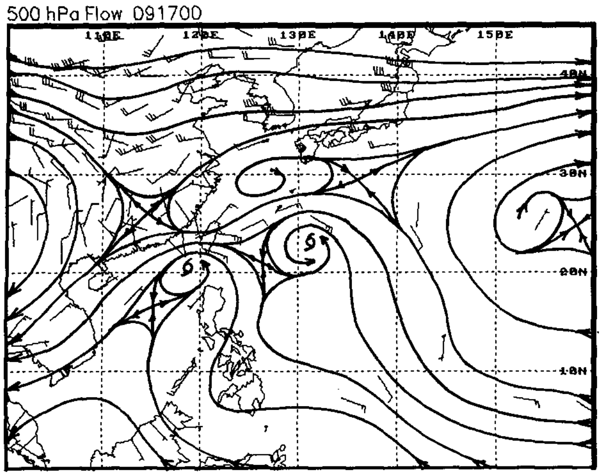


FIG. 4. The 500 hPa flow at 091700.

tem was embedded in a cyclonic shear zone. An example of the large-scale flow as represented by that at 500 hPa is shown in Fig. 4. This situation caused Luke to move initially northwestward and Nat westward. Then Nat turned southward and later eastward due to the adjective flow of Luke. This represents the first directional reversal of Nat. By 091806, Luke was very close to the midlatitude trough (not shown). This changed the large-scale flow in which the binary system is embedded from cyclonic to anticyclonic. As a result, Luke took an abrupt turn toward the northeast. With an increase in separation distance, the mutual interaction between Luke and Nat ended. The movements of these two TCs during their period of interaction (under the influence of first a cyclonic and then an anticyclonic environmental shear) appear to be consistent with the observational as well as the numerical results of Dong and Neumann (1983) and of Chan and Law (1995), respectively.

b. First no-interaction period (091812–092118)

After interacting with Luke, Nat continued to be under the influence of a westerly trough (not shown) and therefore maintained its northeastward course. The environmental steering flow appears to be rather well defined during this period.

c. Nat–Mireille interaction period (092100–092600)

The second directional reversal of Nat occurred shortly after it began to interact with Typhoon Mireille at 092100 when their separation distance was around 1200 km (Fig. 5). At this time, Mireille had an intensity of ~90 kt (45 m s^{-1}) and continued to intensify. Although the synoptic situation is similar to the first part of the Nat–Luke interaction (Fig. 6 compared with Fig. 4), the positions of Nat and Mireille relative to the shear zone were different. In this Nat–Mireille case,

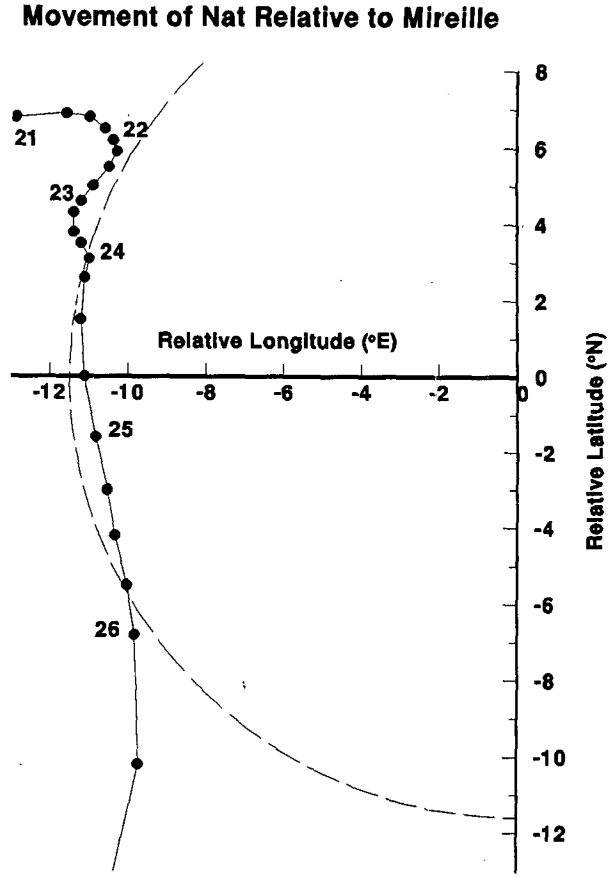


FIG. 5. Six hourly positions of Typhoon Nat relative to the corresponding positions of Supertyphoon Mireille. The numbers along the relative track indicate the 0000 UTC position on that day. The dashed arc has a radius of 11.5° latitude centered on the position of Mireille.

the line connecting the two TCs was oriented northwest–southeast. Such an orientation therefore caused Nat to make an abrupt turn toward the west (the second

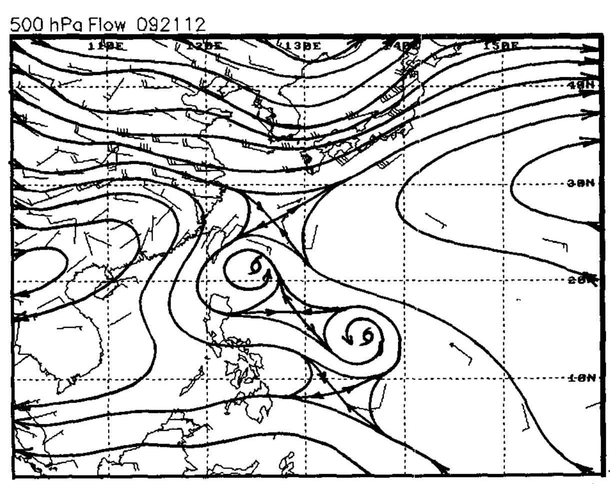


FIG. 6. The 500-hPa flow at 092112.

directional reversal) and Mireille to slow down and track northwestward, again consistent with the findings of Dong and Neumann (1983) and Chan and Law (1995). By 24 September, Nat reached its westernmost position and the two TCs were embedded in the shear zone with almost the same configuration as the case of Nat and Luke (Fig. 7, compared with Fig. 4). It might therefore be expected that Nat would again make a sharp turn. However, although it did turn toward the south (the third directional reversal), it maintained its southward movement for the next 48–60 hours. The difference in the track between the two segments of Nat is probably due to a difference in size and intensity of the other TC: Luke being only a tropical storm, while Mireille reaching supertyphoon intensity by 092400. The circulation associated with Mireille was also more extensive so that the (northerly) advective flow was more intense. This apparently led to a continued southward movement of Nat. By 092600, a westerly trough caused the environmental shear to become anticyclonic (not shown). Therefore, as in the case of Luke, Mireille recurved and stopped interacting with Nat.

d. Second no-interaction period (092600–100200)

After breaking its interaction with Mireille, Nat continued its southward track but weakened to a tropical depression. It then drifted around the area west of Luzon before being lifted northward at 092900 by a deep trough (not shown). It continued to move toward the north until landfall at 100200.

e. Summary

Other than the last direction reversal (which was a case of initial weak steering followed by a strong southerly current associated with a deep westerly trough) and the first no-interaction period, the movement of

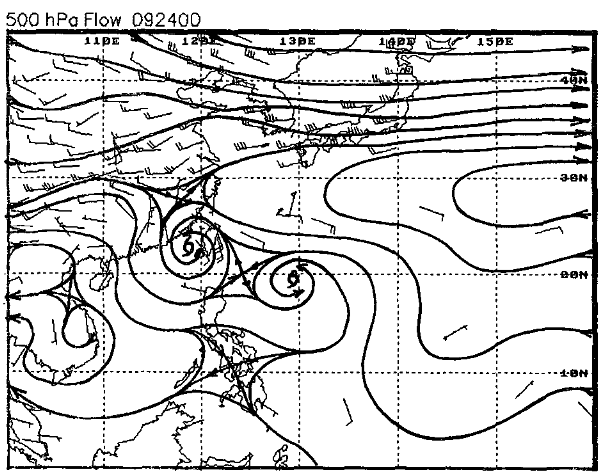


FIG. 7. The 500-hPa flow at 092400.

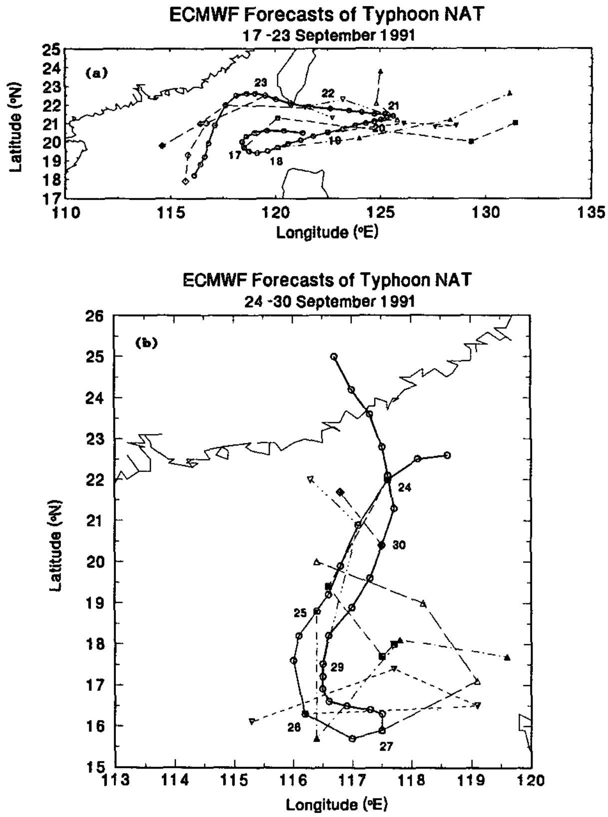


FIG. 8. Forecast positions of Typhoon Nat from the ECMWF model for the period (a) 091712–092312 and (b) 092412–093012. The circles on the thick solid line (which is the best track) represent the six hourly best-track positions with the 1200 UTC position on that day given by the number beside the circle. Each forecast track has a different symbol and a different line type connecting the 24-, 48-, and 72-h positions, with the initial position of each forecast plotted on the best-track position.

Nat was largely determined by its interaction with Luke or Mireille. Therefore, whether the NWP models could make correct predictions of the movement of Nat will depend on the ability of each model to simulate these interactions.

3. The NWP models and the method of locating the predicted TC position

Because this study is concerned with the model performance in TC motion forecasting, only very brief descriptions of the models as related to their treatment of tropical cyclones will be given here. Detailed documentations of each model can be found in the references provided. The method of obtaining the forecast positions of the TC from each of the models is also described.

a. ECMWF model

The ECMWF model is spectral in nature with a truncation of T213 and 31 vertical levels (Simmons et al. 1989; Simmons 1991). The operational model on which the forecasts used in this study are based does not have any bogus observations to represent the TC circulation. In fact, of the five NWP models to be evaluated in this paper, this is the only one without any bogus data. Forecast positions at 24, 48, and 72 h are determined manually from the predicted mean sea level pressure charts by locating a minimum within a certain distance from the best-track position at the verifying time using the method of Chan and Lam (1989).

b. NOGAPS

The NOGAPS consists of a multivariate optimum interpolation analysis and an 18-layer global spectral model with a truncation of T79, which gives a horizontal spacing of around 160 km (Hogan and Rosmond 1991; Goerss and Phoebus 1992). Bogus observations are inserted in the vicinity of a TC based on observed or estimated vortex parameters provided by the warning centers and then forced to be accepted by the analysis scheme. Bogussing is done only for TCs of tropical storm intensity (17 m s^{-1}) or greater. The bogus observations consist of the sum of a symmetric Rankine vortex and an environmental flow, the latter being the spectrally truncated fields at T20. Further details of the bogussing procedure can be found in Fiorino et al. (1993). The predicted positions used in this study were derived from a manual evaluation of the forecast charts. Details of this procedure are described in Georss and Jeffries (1993).

c. UKMO model

The UKMO model is a gridpoint model with a horizontal resolution of around 160 km (Lorenc et al. 1991; Cullen 1993). Bogussing of a TC vortex is done manually by the "intervention forecaster" when no corresponding vortex in the analyzed low-level fields or an analyzed vortex much too weak compared with the information given in the operational warning bulletins is found. A vortex analyzed at a position differing significantly from the warning position will also be shifted to the latter location.

The bogus observations consist of a symmetric wind distribution at 850, 700, and 500 hPa at a few radii from the TC center. The height fields are calculated by the analysis scheme. The UKMO routinely verifies its TC forecasts using an algorithm that identifies the vorticity maximum at the 850-hPa level. Details of the bogussing and verification procedures can be found in Hall et al. (1993). The predicted positions of Nat are those determined from the operational algorithm.

d. TYM

The TYM is a regional model with a horizontal resolution of 50 km at the TC center. It covers an area of 4000 km $\times$ 4000 km and has eight layers in the vertical. The boundary conditions are from the JMA global model. The TYM includes a bogus vortex that consists of an axisymmetric surface pressure field based on the radius of 15 m s^{-1} wind and the central pressure (Iwasaki et al. 1987). Temperatures, *D*-values, and the wind fields associated with this pressure field are then calculated. The large-scale values in the vicinity of the TC are then blended in with the bogus vortex to obtain the final analysis.

Operationally, the JMA issues 12-h forecast positions (up to 60 h) of each TC predicted by the TYM through the Global Telecommunication System (GTS). These are the positions used in the present study.

e. OTCM

The OTCM is the crudest of all the models in this study. It is a regional model with a horizontal resolution of 205 km and only three vertical levels. The boundary conditions are provided by the NOGAPS. A simple Rankine vortex is inserted at the warning position of the TC and maintained throughout the integration with artificial heating (Hodur and Burk 1978). A steering vector estimated from the previous 12-h displacement is also added to the center of the TC as a method of including persistence into the model. The positions of the predicted vortex are determined operationally from the minimum sea level pressure and are the ones used in the present study.

4. Performance of individual models

Before the global and the regional models are compared, it would be useful to study the tracks predicted by each of the models. Attempts will be made to relate the good–bad forecasts to the model characteristics to obtain a better understanding of why the model succeeded–failed. It should be noted, as discussed in the introduction, that in evaluating the accuracy of a forecast, the magnitude of the forecast error is not the only measure. Whether the 24–72-h forecast positions form a reasonable track must also be considered. This is because even if a particular 72-h forecast has a small forecast error, an erratic prediction track from the initial position to the 48-h forecast will render the forecast useless in an operational situation. Therefore, in the following discussion, an interpretation of a forecast being "good" or "bad" carries the above connotation and should not be taken simply as describing a small or large forecast error.

a. ECMWF

Only one ECMWF forecast (091712) exists during the Nat–Luke interaction period, and the prediction was quite poor (Fig. 8a). The model performance improved during the first no-interaction period at least for the 24-h forecast. The predictions from 091912 to 092112 all show a directional reversal, although the westward track of Nat was not predicted. This suggests that the model appears to be capable of predicting the outer circulation of Mireille even though no bogus vortex was inserted. A possible reason for this to occur is due to the intensity and size of Mireille. In fact, the model accuracy further increased for the forecasts issued between 092212 and 092412 (Figs. 8a and 8b). Although the 24-h forecast from 092512 is quite good, the 48- and 72-h forecasts from the same initial time are inaccurate in terms of direction (although the forecast errors may be acceptable). These latter times correspond to the period when Nat began to lose its interaction with Mireille and stayed in a region of weak steering. The forecasts from 092612 were also quite erratic. While the 24-h forecast from 092712 was rather inaccurate, the overall track predicted from the analysis initialized at this time gave the correct northward trend. In fact, the 72-h forecast was within 2° latitude from the best-track position. The forecasts from 092912 and 093012 were all quite good.

To summarize, while the ECMWF model could not predict the Nat–Luke interaction, the Nat–Mireille interaction was quite well predicted, especially in the later stage. However, during the period of weak steering, although the magnitudes of the forecast error are not excessively large, the predicted tracks are very erratic, making its operational utility questionable. Some of these results are consistent with the conclusion of Chan and Lam (1989) in their analysis of Typhoon Wayne of 1986. That is, the model performs well when the synoptic-scale flow is well defined or when the TC is not interacting with another TC. However, the fact that the model predictions were quite good during the latter part of the Nat–Mireille interaction period suggests that the model predictions may still be useful in binary interaction situations if the outer circulations of the vortices can be correctly analyzed, which is the usual situation when the TCs are large or intense. Nevertheless, the improvements in the model accuracy of TC motion forecasting do not seem to be concomitant with those implemented in the ECMWF model during the last few years (convection and radiation schemes, increase in resolution, etc.). A possible reason for this lack of significant increase in skill may be the absence of a good representation of the vortex in the model. Such a representation is especially important when the TC circulation is not extensive so that observations far from the TC center cannot provide information about the structure or even the existence of a TC. More discussion of this point will be given later.

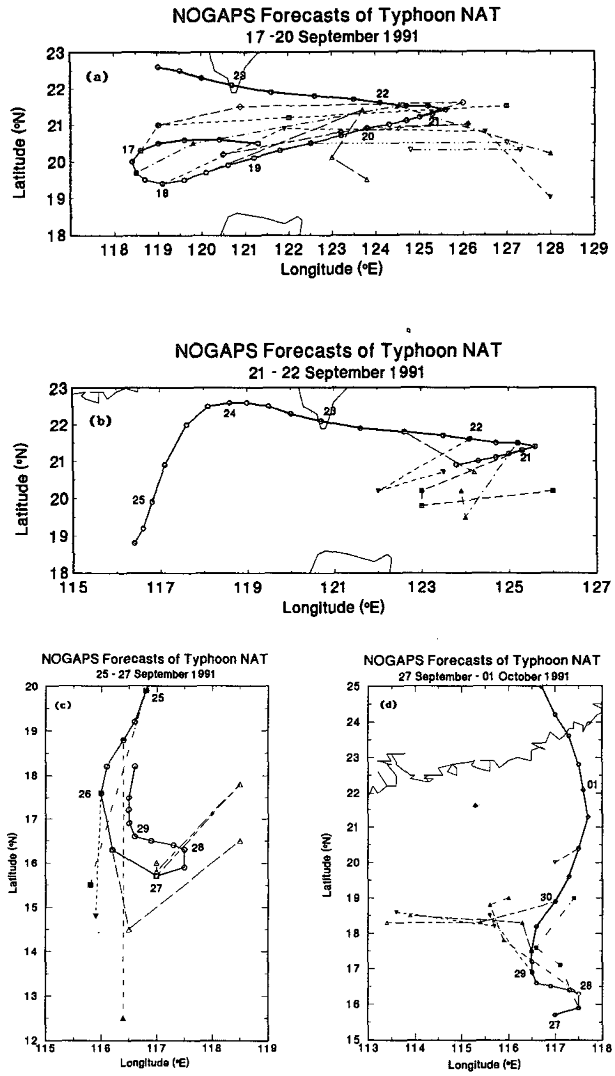


FIG. 9. Forecast positions of Typhoon Nat from the NOGAPS model for the period (a) 091700–092012, (b) 092100–092212, (c) 092500–092700, and (d) 092712–100100. The circles on the thick solid line (which is the best track) represent the 6-h best-track positions with the 0000 UTC position on that day given by the number beside the circle. Each forecast track has a different symbol and a different line type connecting the 24-, 48-, and 72-h positions, with the initial position of each forecast is plotted on the best-track position.

b. NOGAPS

Although the NOGAPS forecasts from 091700 were not able to predict the first directional reversal, those from 091712 and 091800 did suggest that Nat would take on a northeastward movement (Fig. 9a). During the first no-interaction period, the 24-h forecasts were quite good and the 48- and 72-h forecasts starting from 091812 show a directional reversal. Although it was incorrect, this sudden change suggests again that the predicted NOGAPS fields associated with Mireille is having an influence on the predicted movement of Nat. Indeed, the model successfully predicted the second directional reversal at 092012. However, the next four predictions were highly incorrect (Fig. 9b). The center-locating algorithm was unable to find a predicted center of Nat for the period 092300–092412. The model did predict a southward movement of Nat from the analyses between 092500 and 092612, although with excessive speed (Fig. 9c). The model was rather successful in predicting the fourth directional reversal of Nat, but a strong leftward bias is found during the final stages of Nat (Fig. 9d).

The bogus observations inserted into the NOGAPS analysis seemed to have contributed to more accurate model forecasts during the first interaction period. However, after the success of predicting the second directional reversal, the model performance was poor during the second interaction period. This could be due to an incorrect bogus vortex for Nat and/or Mireille. On the other hand, the presence of a well-defined vortex circulation during the time of weak steering may have contributed to the success of the model in predicting the fourth directional reversal. It is also worth noting that the NOGAPS predictions during the later stage of the second no-interaction period are considerably poorer than those of the ECMWF, suggesting that perhaps the large-scale flow was not too well predicted by the NOGAPS.

c. UKMO

Of the five models evaluated in this paper, only the UKMO provides the position of the analyzed vortex. These are plotted in Fig. 10 together with the predicted positions even though Chan and Kay (1993) have found that large initial position errors do not seem to have a significant impact of the long-term UKMO model forecasts.

The 48- and 72-h forecasts made between this time and 092100 were not particularly good. The model successfully predicted a southward and southeastward movement based on the 091700 and the 091712 analyses, respectively (Fig. 10a). However, the predictions during the first no-interaction period went too far to the east. Although the second directional reversal was correctly predicted from 092000 (Fig. 10b), the 48- and 72-h forecasts made between this time and 092100 were not particularly good. Beginning at 092112, the model correctly predicted the westward then southward movement of Nat. Similarly, the third directional reversal was correctly predicted at 092400 (Fig. 10c). Unfortunately, no forecast position could be identified by the algorithm during the fourth directional reversal, possibly because of the low intensity of Nat. The model did not perform very well during the last stage of Nat (Fig. 10d).

Of all the three global models, the UKMO appears to have the best performance in predicting the first three directional reversals, which might at least partly be attributed to the bogus vortex in the UKMO model. However, the UKMO predictions seem to be inferior to those of ECMWF during the times when the large-scale flow was well-defined.

d. TYM

With the exception of the forecasts made at 091600, the TYM was capable of capturing the first directional

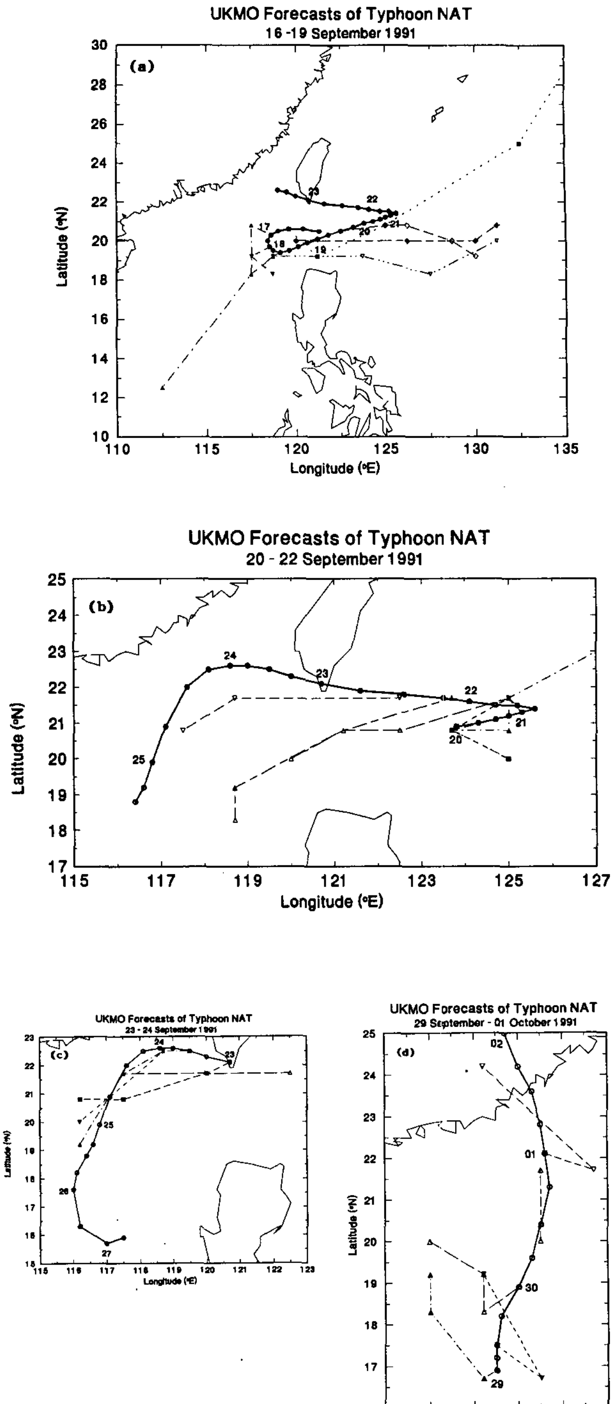
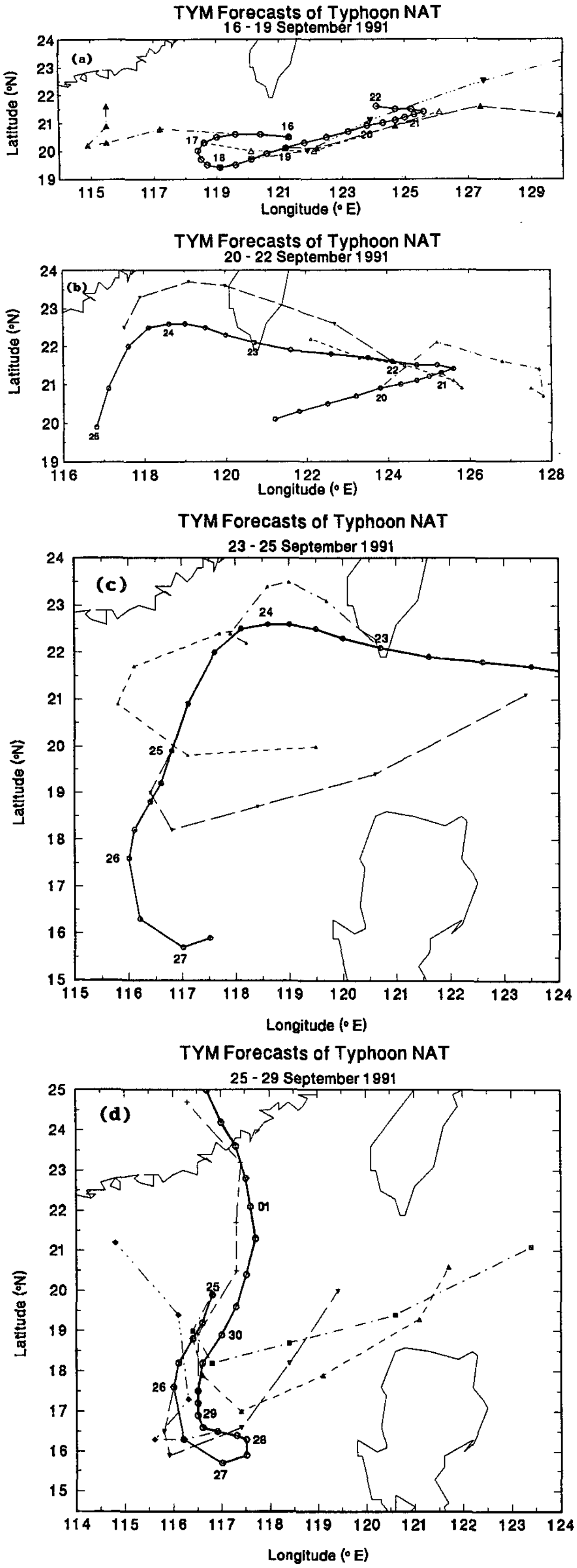


FIG. 10. Forecast positions of Typhoon Nat from the UKMO model for the period (a) 091700–091912, (b) 092000–092212, (c) 092300–092412, and (d) 092900–100100. The circles on the thick solid line (which is the best track) represent the 6-h best-track positions with the 0000 UTC position on that day given by the number beside the circle. Each forecast track has a different symbol and a different line type connecting the 24-, 48-, and 72-h positions. The initial position of each forecast can be different than the best-track position and is plotted using the same symbol and connected to the latter using the same line type as the forecast positions.



reversal of Nat (Fig. 11a). The errors for the 091600 could be due to an incorrect bogus as Nat was only a tropical depression at this time. Although the 24-h forecast from 091800 was very good, the TYM predicted a subsequent northeastward acceleration that did not occur. A similar situation exists for the 091900 forecasts. However, notice a sudden change in the long-term (>48 h) forecast track in the 092000 forecasts (Fig. 11b). Apparently, the model predicted that Mireille would be close enough to Nat so that an interaction between the two TCs would begin. Indeed, the forecasts made at 092100 did predict a directional reversal of Nat, though delayed by about 24 h when compared with the observed track. The interaction of Nat and Mireille was clearly predicted by the model as seen from the cyclonically rotated forecast tracks during the interaction period (Figs. 11b–d), although the model apparently predicted Nat would turn eastward sooner and faster. The performance of the TYM was also quite good in predicting the northward movement of Nat during its last stage (Fig. 11d).

To summarize, the TYM appears to be quite successful in predicting the interaction between two TCs, during both the Nat–Luke and Nat–Mireille interaction periods. This ability is apparently related to the two characteristics of the model: its high resolution and the bogus vortex.

e. OTCM

The OTCM was unable of predicting the interaction between Nat and Luke or the first directional reversal (Fig. 12a). The predictions were better during the first no-interaction period, although, similar to the TYM, the speeds were exceedingly high (Fig. 12b). Apparently because of the imposed initial steering, the model predicted Nat to continue a northeastward track at the beginning of the Nat–Mireille interaction period (Fig. 12c). By 092118, the persistence component finally allowed the model to predict Nat to move westward. Similar situations occurred in the next two days, although the model continued to predict Nat to turn northward (Figs. 12d–e), apparently in response to the westerly trough to the north of Nat (see Fig. 6). The best OTCM forecasts seem to occur for those made between 092600–092800 in which the fourth directional reversal was correctly predicted (Figs. 12e–f). During

FIG. 11. Forecast positions of Typhoon Nat from the TYM model for the period (a) 091600–091900, (b) 092000–092200, (c) 092300–092500, and (d) 092512–092912. The circles on the thick solid line (which is the best track) represent the 6-h best-track positions with the 0000 UTC position on that day given by the number beside the circle. Each forecast track has a different symbol and a different line type connecting the 12-, 24-, 36-, 48-, and 60-h positions, with the initial position of each forecast plotted on the best-track position.

the last stage of Nat, the OTCM forecasts has a very obvious westward bias (Figs. 12f,g).

Thus, even with a bogus vortex in the OTCM, the model failed badly in predicting the binary interaction process. One possible problem in this case is that the initial motion of the vortex is forced by persistence, which for binary cyclones may not be a good estimator of short-term motion. Furthermore, in OTCM, the bogus vortex only exists for the TC that the model is predicting. Therefore, the model does not have any additional bogus data for Mireille when predicting the motion of Nat. Thus, OTCM is probably a bad choice when it comes to predicting the movement of binary cyclones.

f. Summary

The examination of the forecast tracks of the three global and two regional models in predicting the movement of Nat point to the following characteristics of models that may have contributed to their success–failure.

(a) A bogus vortex apparently helps in predicting the binary interaction, provided that it has a structure representative of the actual TC, and bogussing should be done simultaneously for both TCs so as to simulate their mutual interaction.

(b) An increase in resolution may be a contributing factor in increasing the accuracy of the model.

(c) The large-scale flow associated with TC motion is apparently better predicted by the global model.

(d) Simple persistence imposed on the model vortex may be detrimental in binary interaction predictions.

Inferences (a) and (c) are consistent with the findings of Chan and Lam (1989), while point (b) has been suggested as a way to improve the accuracy of NWP models in predicting TC motion (Krishanamurti et al. 1993). The last inference, if true, has important implications in determining how bogussing should be done in NWP models.

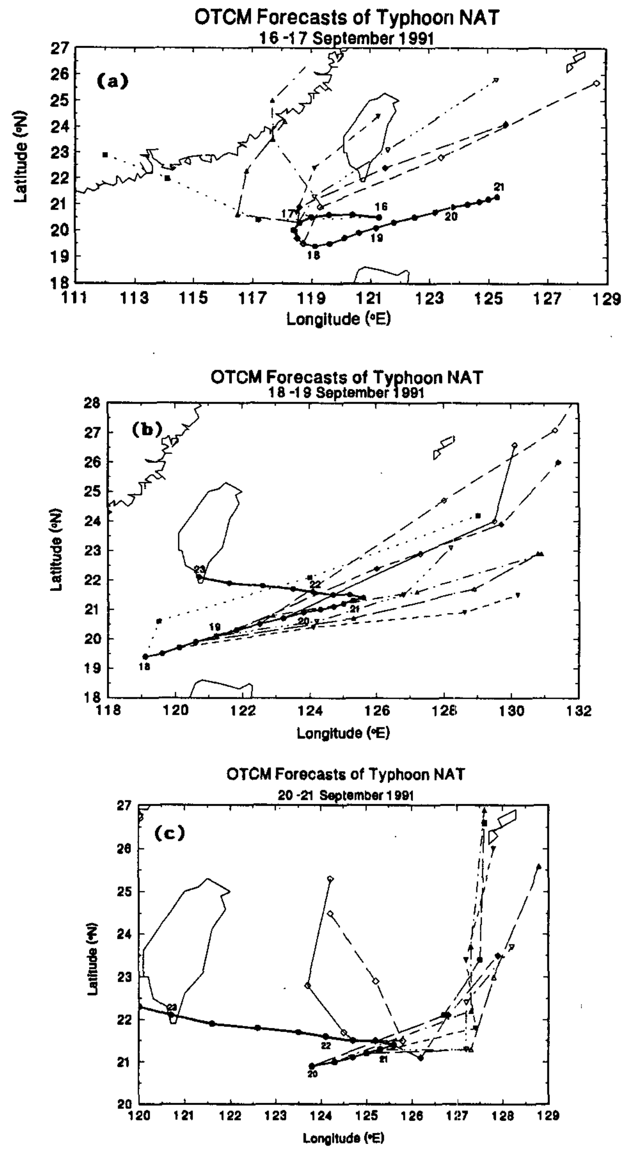


FIG. 12. Forecast positions of Typhoon Nat from the OTCM model for the period (a) 091600–091712, (b) 091800–091912, (c) 092000–092112, (d) 092200–092312, (e) 092400–092700, (f) 092800–092912, and (g) 093000–100112. The circles on the thick solid line (which is the best track) represent the six hourly best-track positions with the 0000 UTC position on that day given by the number beside the circle. Each forecast track has a different symbol and a different line type connecting the 24-, 48-, and 72-h positions, with the initial position of each forecast plotted on the best-track position.

5. Summary and conclusions

Chan and Lam (1989) considered the track of Typhoon Wayne (1986) to be exceptionally rare and therefore examined the performance of the ECMWF model in predicting its movement. They found that the model failed when Wayne was interacting with another typhoon or in a region of weak steering flow. Five years later, another typhoon, Nat (1991), made the same number of direction reversals, three of which were due to its interaction with two other TCs and the other resulting from weak steering. This paper presents the analyses of the performance of not just one, but five (three global and two regional), NWP models in predicting the movement of Nat.

It is found that because of the ability of the global models in predicting the large-scale flow, the movement of Nat was in general better predicted by them than by the regional models. However, an increase in resolution and a bogus vortex representative of the structure of Nat apparently helped the TYM produce some rather good forecasts. These two factors, a representative bogus vortex and high resolution, also appear to have contributed to the good forecasts of the UKMO and ECMWF models, respectively. The reasons for the poor performance of the OTCM include an imposed

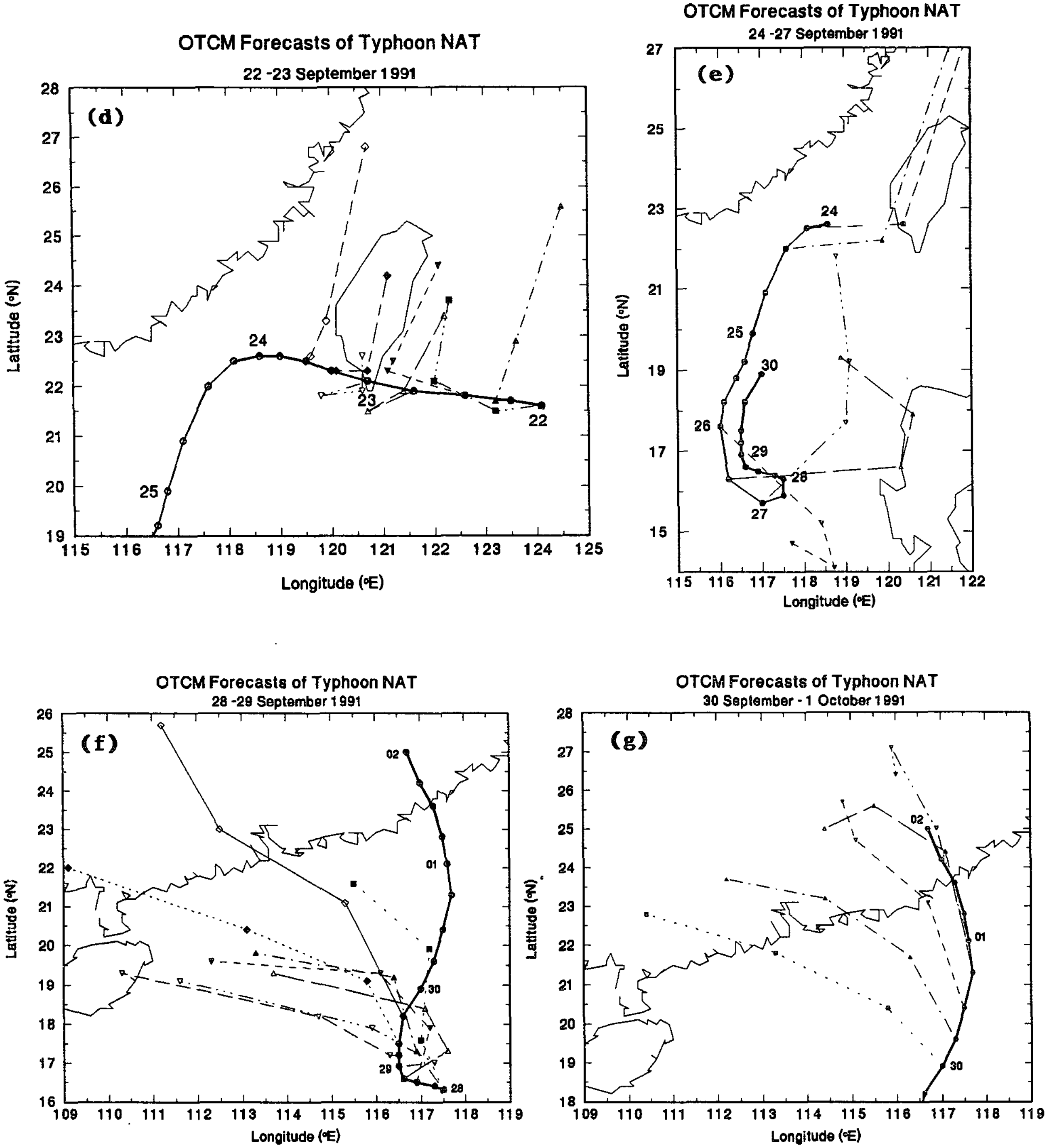


FIG. 12. (*Continued*)

steering, its coarse resolution, and a single bogus vortex for each TC.

Although the UKMO and the NOGAPS models have similar resolutions and both incorporate bogus vortices, their performance differed. This suggests that the bogus vortex must have a structure similar to that of the actual TC. It is also interesting to note that the ECMWF model had many good forecasts despite the absence of any bogus information. However, as pointed out in section 4a, this model was able to make reasonable predictions only when the circulation of Mireille became extensive. Therefore, even with the high resolution and perhaps a better cumulus parameterization scheme, the lack of a bogus vortex still appears to reduce the utility of the model forecasts. This conclusion may appear to contradict the recent findings of Serrano and Undén (1994), who also studied the interaction of Nat with Mireille and Luke by inserting a simple bogus vortex. They found that the ECMWF predictions beyond 24–28 h actually deteriorated with the inclusion of bogus data. However, this might be due an incorrect bogus, as suggested by the authors.

While the inferences from the present results are drawn from only one single case study, they appear to be physically reasonable. These inferences are also consistent with previous studies such as Chan and Lam (1989) and Peng et al. (1994) on the need for a proper bogus vortex in the model and Shun (1992) and Krishnamurti et al. (1993) on the improvements in model forecasts with increasing resolution. The results from this case study therefore further substantiate the conclusions of these previous researchers.

Of course, to confirm the above inferences, sensitivity tests of the models are necessary. However, such studies are beyond the scope of the present study. The other option is to perform a more comprehensive study of the model performance for all different types of synoptic situations.

Acknowledgments. The author would like to acknowledge the contributions from the following groups or individuals: Pat Phoebus and Jim Goerss of the Naval Research Laboratory, Monterey, California, for providing the NOGAPS and OTCM forecasts; C. M. Shun and K. P. Wong of the Royal Observatory, Hong Kong, for providing copies of the ECMWF forecast charts and the GTS messages (for extracting the TYM forecasts), respectively; Alan Radford of the UKMO for providing the UKMO forecasts; and Simon L. Y. Chan and Qiuqing Zhang for extracting some of the forecast positions. Mr. Simon Chan also helped develop some of the graphics in this paper. The author also benefited from discussions he had with Dr. Mark Lander of University of Guam on the NOGAPS analyses and forecasts. The manuscript was professionally prepared by Ms. Betsy M. K. Yu.

This research is supported by the Indicated Research Grant No. 700071 of the City Polytechnic of Hong Kong and partially supported by the Office of Naval Research Grant N00014-92-J-1042.

REFERENCES

Chan, J. C. L., and H. Lam, 1989: Performance of the ECMWF model in predicting the movement of Typhoon Wayne (1986). *Wea. Forecasting,* **4,** 234–245.

——, and W. K. Kay, 1993: Performance of the United Kingdom Meteorological Office global model in predicting the movement of tropical cyclones. *Wea. Forecasting,* **8,** 326–336.

——, and A. C. K. Law, 1995: The interaction of binary vortices in a barotropic model. *Meteor. Atmos. Phys.,* in press.

Cullen, M. J. P., 1993: The unified forecast/climate model. *Meteor. Mag.,* **122,** 81–94.

Dong, K., and C. J. Neumann, 1983: On the relative motion of binary tropical cyclones. *Mon. Wea. Rev.,* **111,** 945–953.

Fiorino, M., J. S. Goerss, J. J. Jensen, and E. J. Harrison, 1993: An evaluation of the real-time tropical cyclone forecast skill of the Navy Operational Global Atmospheric Prediction System in the western North Pacific. *Wea. Forecasting,* **8,** 3–24.

Goerss, J. S., and P. A. Pheobus, 1992: The Navy's operational atmospheric analysis. *Wea. Forecasting,* **7,** 232–249.

——, and R. A. Jeffries, 1993: Assimilation of synthetic tropical cyclone observations into the Navy Operational Global Atmospheric Prediction System. *Wea. Forecasting,* **9,** 557–576.

Hall, C. D., J. C. R. Hurt, A. M. Radford, D. J. Carruthers, and W. S. Weng, 1993: Forecasting tropical cyclones and near surface wind conditions. *Tropical Cyclone Disasters,* J. Lighthill, Z. Zheng, G. Holland, and K. Emanuel, Eds., Peking University Press, 232–257.

Hodur, R. M., and S. D. Burk, 1978: The Fleet numerical weather central tropical cyclone model: Comparison of cyclic and one-way interactive boundary conditions. *Mon. Wea. Rev.,* **106,** 1665–1671.

Hogan, T. F., and T. E. Rosmond, 1991: The description of Navy operational global atmospheric prediction system's spectral forecast model. *Mon. Wea. Rev.,* **119,** 1786–1815.

Iwasaki, T., H. Nakano, and M. Sugi, 1987: The performance of a typhoon track prediction model with cumulus convection. *J. Meteor. Soc. Japan,* **65,** 555–570.

Krishnamurti, T. N., H. S. Bedi, K. S. Yap, and D. Oosterhof, 1993: Hurricane forecasts in the FSU models. *Adv. Atmos. Sci.,* **10,** 121–131.

Lorenc, A. C., R. S. Bell, and B. Macpherson, 1991: The Meteorological Office analysis correction data assimilation scheme. *Quart J. Roy. Meteor. Soc.,* **117,** 59–90.

Neumann, C. J., and J. M. Pelissier, 1981: An analysis of Atlantic tropical cyclone forecast errors. *Mon. Wea. Rev.,* **109,** 1248–1266.

Peng, M. S., D. S. Chen, S. W. Chang, C. P. Chang, and B. F. Jeng, 1994: Improvement of numerical prediction of typhoon tracks in the western North Pacific Basin near Taiwan. *Wea. Forecasting,* **10,** 409–422.

Serrano, E., and P. Undén, 1994: Evaluation of a tropical cyclone bogusing method in data assimilation and forecasting. *Mon. Wea. Rev.,* **122,** 1523–1547.

Shun, C. M., 1992: Performance of the ECMWF model in tropical cyclone track forecasting over the western North Pacific during 1990–1991. Tech. Memo. No. 184, ECMWF, Reading, UK, 32 pp.

Simmons, A. J., 1991: Development of a high-resolution semi-Lagrangian version of the ECMWF forecast model. ECMWF Tech. Report No. 180, ECMWF, Reading, UK, 45 pp.

——, D. M. Burridge, M. Jarraud, C. Girardan, and W. Wergen, 1989: The ECMWF medium-range prediction models. Development of the numerical formulations and the impact of increased resolution. *Meteor. Atmos. Phys.,* **40,** 28–60.