TROPICAL FORECASTING WITH GLOBAL MODELS

Johnny C. L. Chan
Department of Applied Science, City Polytechnic of Hong Kong
Kowloon, HONG KONG

1. INTRODUCTION

In the not-so-distant past, global numerical weather prediction (NWP) models were mostly developed for and used by meteorologists in the mid-latitudes. The recent increase in the understanding of the interactions between the tropics and the extratropics has led to an emphasis on the representation of physical processes in the tropics in the global models. As a result, predictions by these models of tropical weather phenomena have generally improved and more tropical weather forecasters are using such predictions for guidance. In contrast with the forecasts of mid-latitude weather systems (which are continuously monitored by the global centres), very few evaluations of the tropical forecasting skill of global models exist.

In this paper, some aspects of the performance of global models in tropical forecasting will be examined. Because the most important tropical weather system on a synoptic scale is the tropical cyclone (TC), the bulk of this paper will be devoted to the forecasting of TCs by global models. A case study will first be presented in Section 2 to illustrate the strengths and weaknesses of the models in TC track forecasting. A summary of the methods used by different operational NWP centres to tackle a fundamental problem of global models in TC track forecasting - the representation of the TC circulation in the model - will be given in Section 3. While most of the research on TC forecasting by global models has been focussed on the movement aspect, a few studies of global model predictions of the formation of TCs have been made. These results will be briefly described in Section 4. Tropical cyclones are not only important by themselves but can interact with extratropical systems as well. A case study of such an interaction will be presented in Section 5 to emphasize the need for further improvements in TC forecasting of global models. The paper will conclude in Section 6 with a discussion on the future research in the tropical forecasting ability of global models.

2. FORECASTING OF TYPHOON WAYNE BY THE ECMWF MODEL

Typhoon Wayne (1986) was one of the most unusual tropical cyclones in the western North Pacific. Formed on the evening of 17 August 1986, it roamed the northern part of the South China Sea and waters near Taiwan for the next three weeks. During its lifetime, Wayne made four major directional reversals (Fig. 2.1) and presented forecasters with great problems in predicting its movement. It is therefore worthwhile to analyze how the European Centre for Medium-Range Weather Forecasts (ECMWF) model performed in forecasting the movement of Wayne.

The discussion will be divided into four parts corresponding to the four direction reversals. The synoptic background leading to the changes in track will also be briefly described. The ECMWF forecasts as determined from the 100-kPa wind prognoses will be compared with those operationally made at the Royal Observatory, Hong Kong (RO). For a detailed description of the procedures in determining the forecast positions, the reader is referred to Chan and Lam (1989).

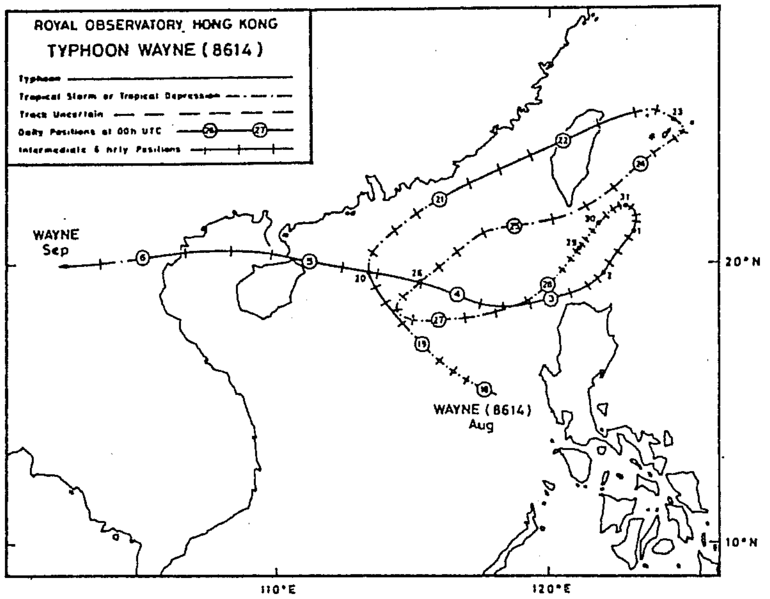

Fig. 2.1 Best-track of Typhoon Wayne as derived from post-analysis by the Royal Observatory, Hong Kong.

2.1 *18-20 August*

The 500 hPa streamline analysis for 1200 UTC on 19 August[1] shows the subtropical ridge to the north of Wayne and the westerlies more than 10° latitude from Wayne (Fig. 2.2*a*). A TC under such conditions is normally not expected to recurve. However, 12 h later, the subtropical ridge split apart (Fig. 2.2*b*) and Wayne turned sharply towards the northeast at around 2000.

The best track for this segment and the RO and ECMWF forecast positions are shown in Fig. 2.3. Notice that while the RO forecasts had a strong persistence component, the ECMWF model predicted recurvature at the critical time 1912. After the recurvature, the ECMWF model on 20 August also predicted that Wayne would return to the South China Sea

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[1] For convenience, a 4-digit number DDHH will be used to refer to the time in this paper, where DD represents the day and HH the hour in UTC. For example, 1912 represents 1200 UTC on 19 August.

Although Wayne did not enter the South China Sea until 2500, the model predictions gave the correct trend.

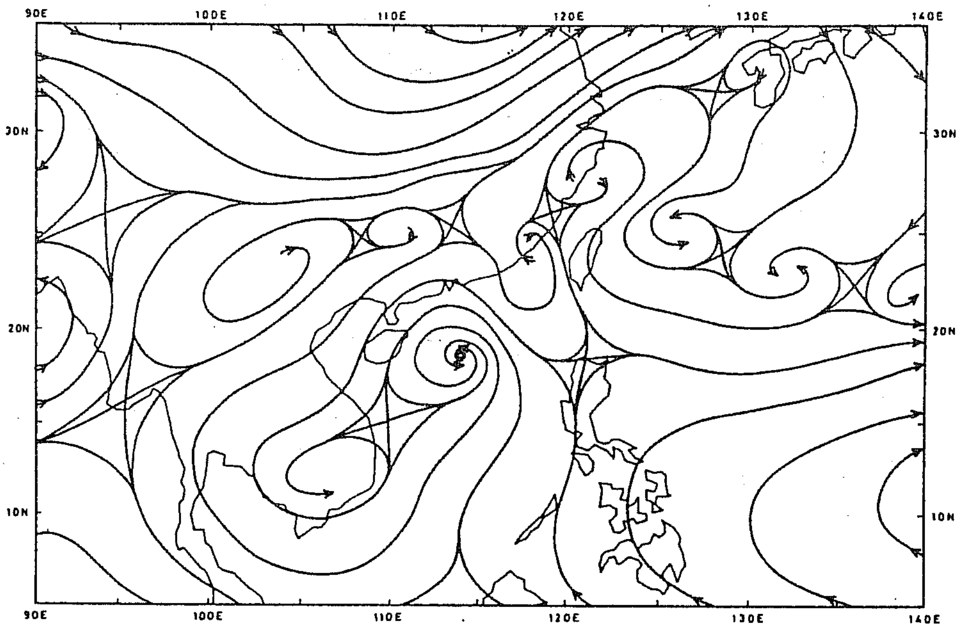

Fig. 2.2a. 500 hPa streamline analysis at 1912.

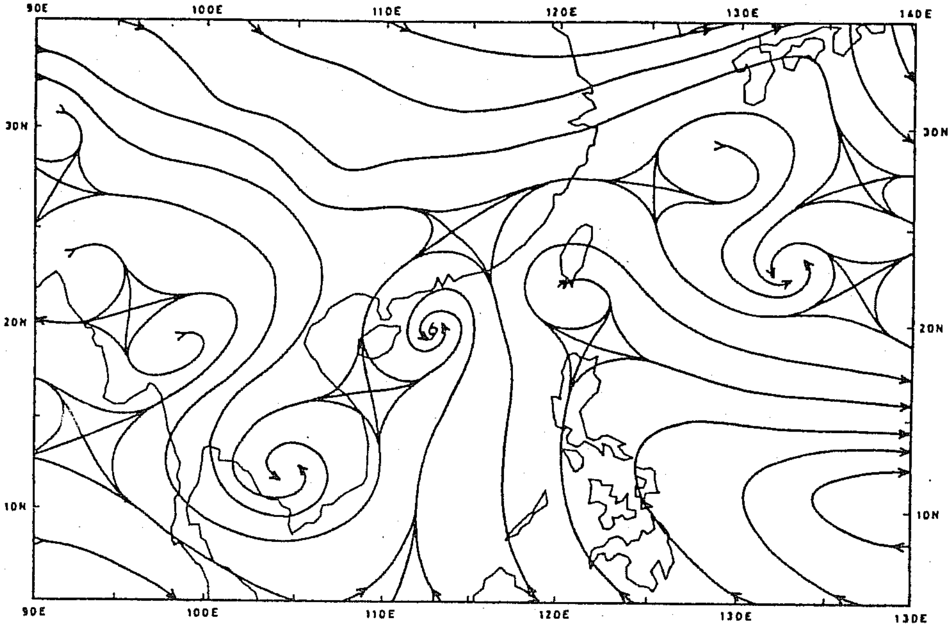

Fig. 2.2b. 500 hPa streamline analysis at 2000.

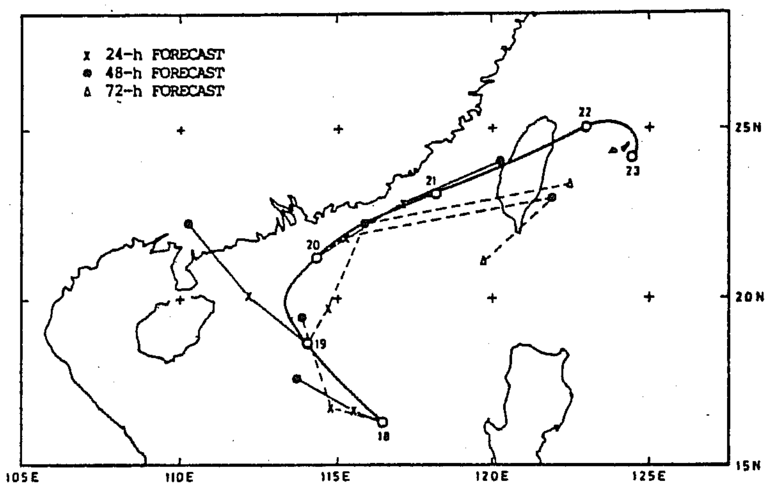

Fig. 2.3. The best-track segment of Wayne (thick solid) between 1812-2012 and the forecast tracks of the RO (thin solid) and those based on the ECMWF winds (dashed). Numbers in the circles along the best track indicate the day at 1200 UTC.

2.2 21-23 August

Around 2212, the westerlies retreated northwards (not shown). As a result, Wayne began to slow down and turned southeastwards. A 500 hPa anticyclone developing over China (Fig. 2.4) then "steered" Wayne southwestwards at around 2306.

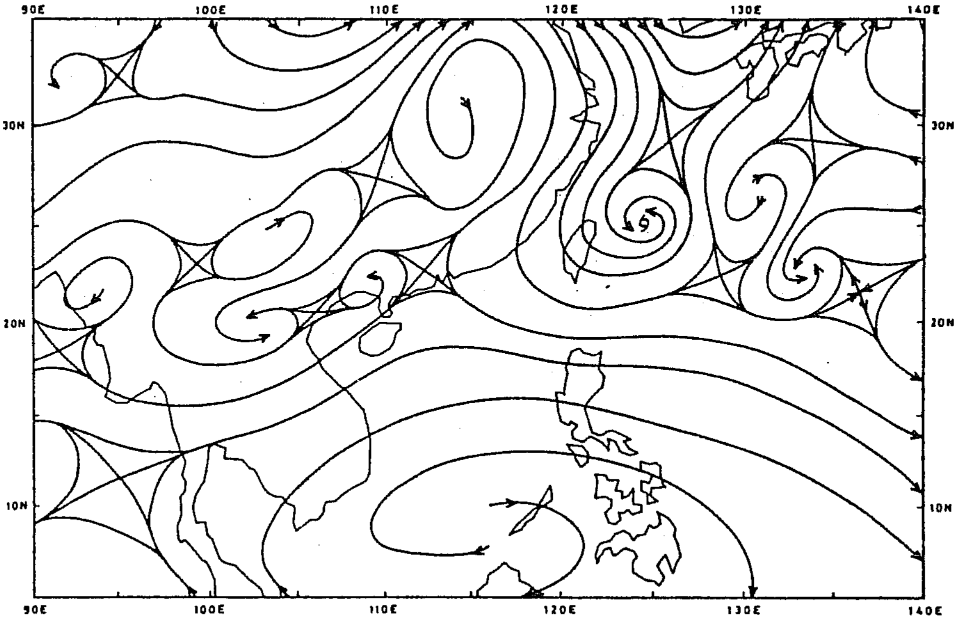

Fig. 2.4. 500 hPa streamline analysis at 2300.

The RO forecasts during this period (Fig. 2.5) indicate the large errors that can occur when a forecast of recurvature does not verify. The 48-h forecast errors made by the RO at and 2312 were > 1000 km. However, the ECMWF forecasts indicated a directional reversal for both the 2112 and 2212 forecasts. At the critical time 2212, the 72-h forecast errors were < 200 km. Further, the 2312 forecast suggested a continued southwestward movement. The ECMWF model therefore performed extremely well during this period.

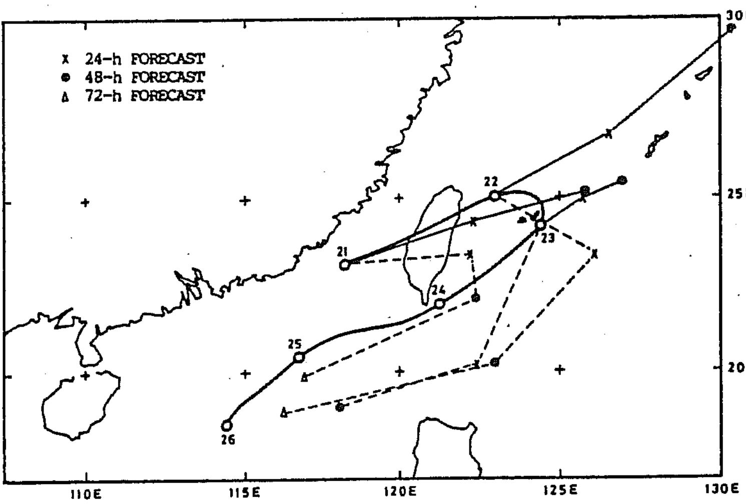

Fig. 2.5. As in Fig. 2.3 except for the period 2112-2312.

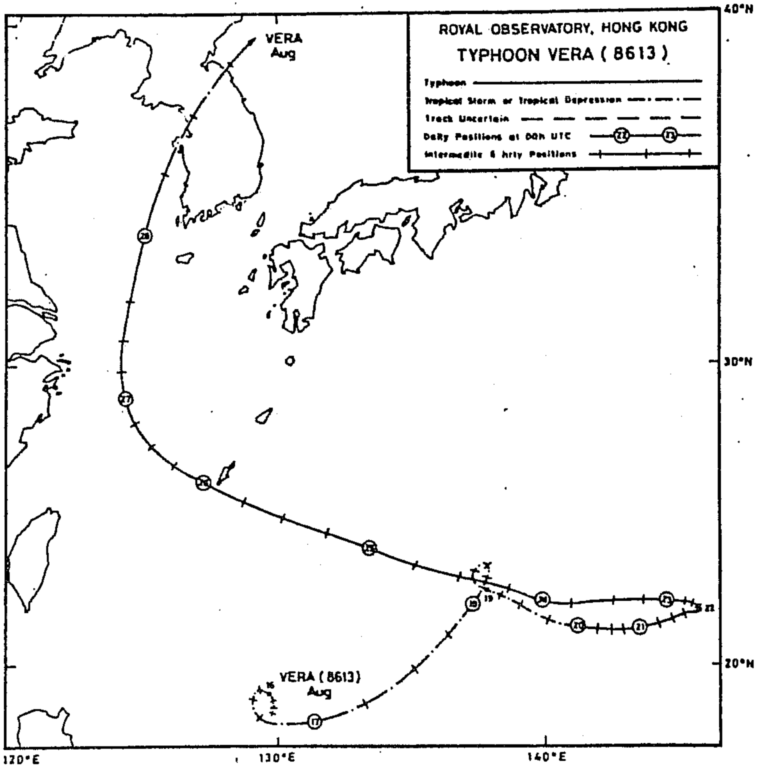

Fig. 2.6. Best-track of Typhoon Vera as derived from post-analysis
by the Royal Observatory, Hong Kong.

2.3 24-27 August

While Wayne was heading towards the southwest, another typhoon at around 140°E, Vera, was moving west-northwestwards (Fig. 2.6). Because the circulation of Vera much larger than that of Wayne, the 'Fujiwhara' effect between the two cyclones was such that Wayne was under the influence of Vera from around 2400 to 2718. As can be seen from Fig. 2.7, Wayne moved cyclonically around Vera during this period at a radius of about 1 500 km with an average rotational speed of about 20° per day. As Vera recurved to the north over the East China Sea at 2612, the interaction between the two cyclones caused Wayne to slow down and begin to turn eastwards. The sharp turn towards the east at around 2618 as a result of the Fujiwhara interaction represents the third directional reversal of Wayne.

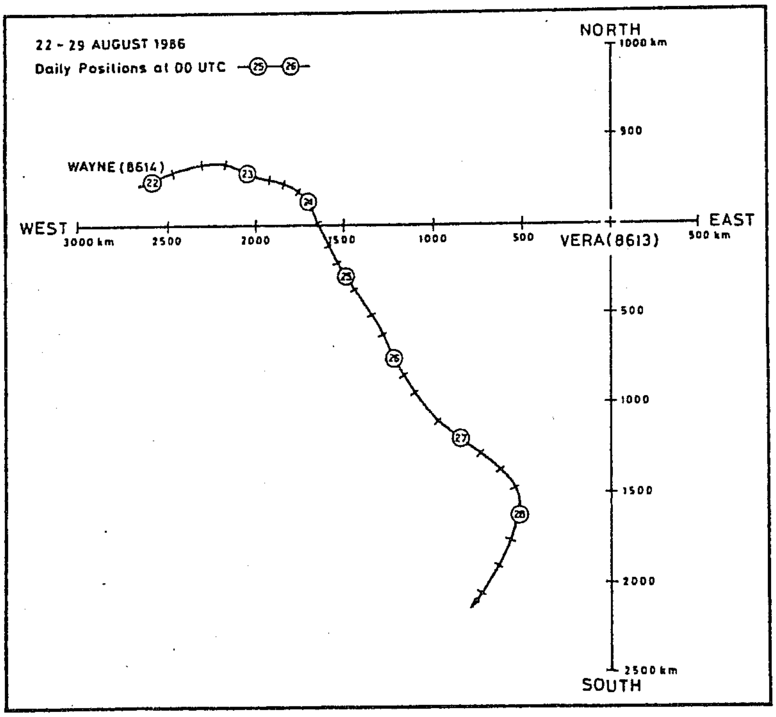

Fig. 2.7. Movement of Typhoon Wayne relative to Typhoon Vera between 22-29 August 1986.

The ECMWF forecasts during this period were not as satisfactory as those in the previous two periods (Fig. 2.8). The directional reversal that occurred at around 2612 was not predicted. An abrupt turn in the forecast track also occurred in the 2712 predictions, giving rise to rather inaccurate forecasts. This result is quite discouraging as it implies that the ECMWF model may not be capable of predicting the interaction between two TCs. Morris (1989) also had a similar conclusion in his study of the performance of the UK Meteorological

Office (UKMO) global model in forecasting TCs in the South Indian Ocean and the Australian region.

For the RO forecasts, an interaction between Wayne and Vera was anticipated at 2412 so that a southward and then southeastward movement was predicted. However, Wayne moved much more towards the southwest before recurving back eastwards.

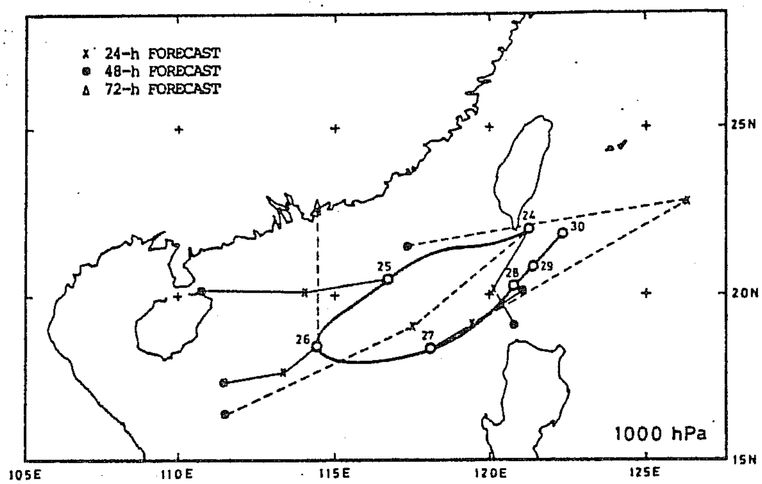

Fig. 2.8. As in Fig. 2.3 except for the period 2412-2712.

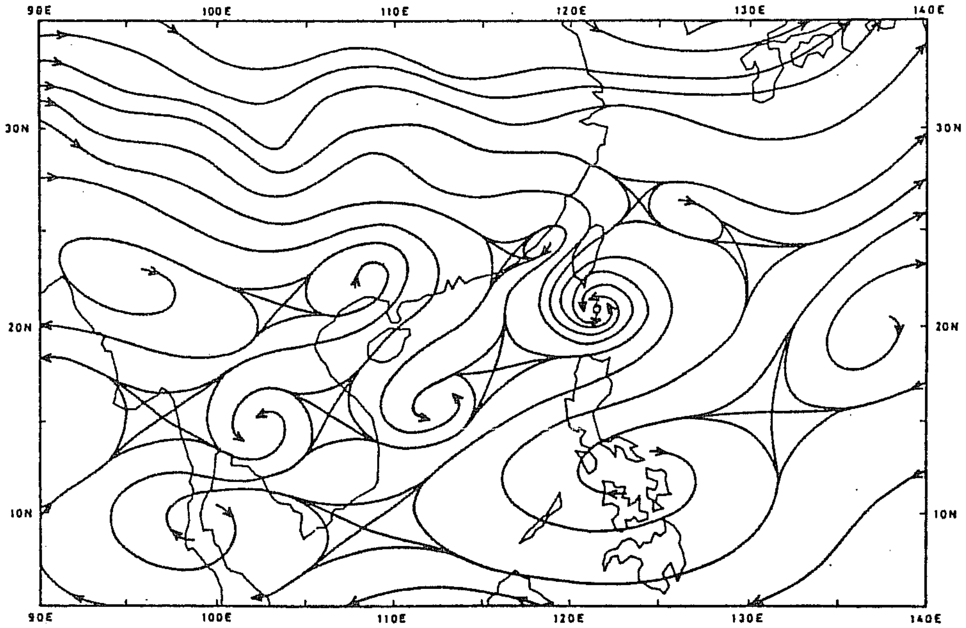

Fig. 2.9. 500 hPa streamline analysis at 2912.

2.4 *28 August - 1 September*

At 2912, the 500 hPa flow pattern shows that Wayne was surrounded by anticyclones (Fig. 2.9). As a result, Wayne became quasi-stationary over the waters just to the southeast of Taiwan. These conditions persisted for the next two days. The fourth directional reversal of Wayne occurred at around 0100 when the 500 hPa anticyclone over south China became more dominant (Fig. 2.10).

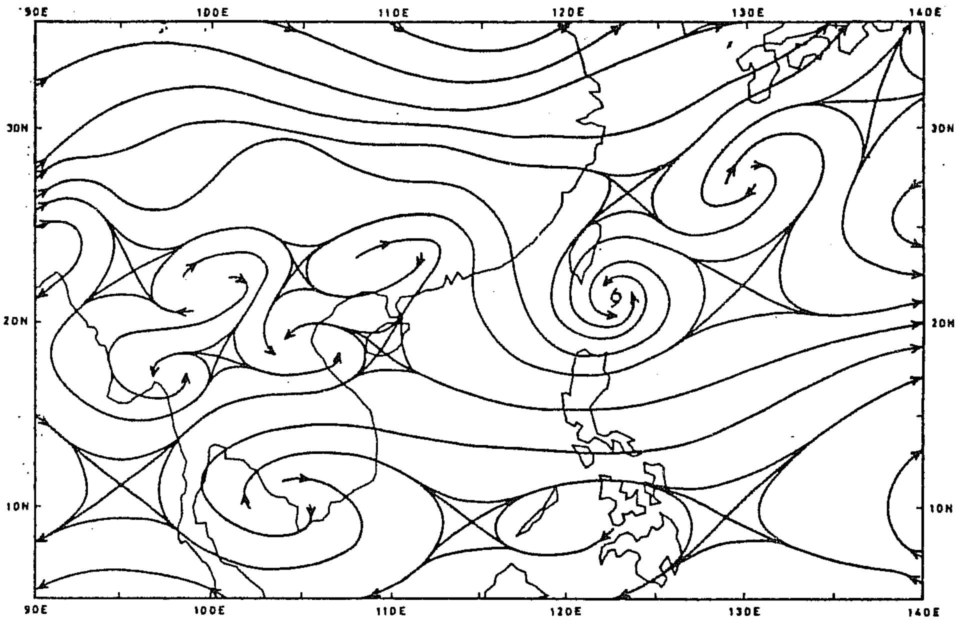

Fig. 2.10. 500 hPa streamline analysis at 0100.

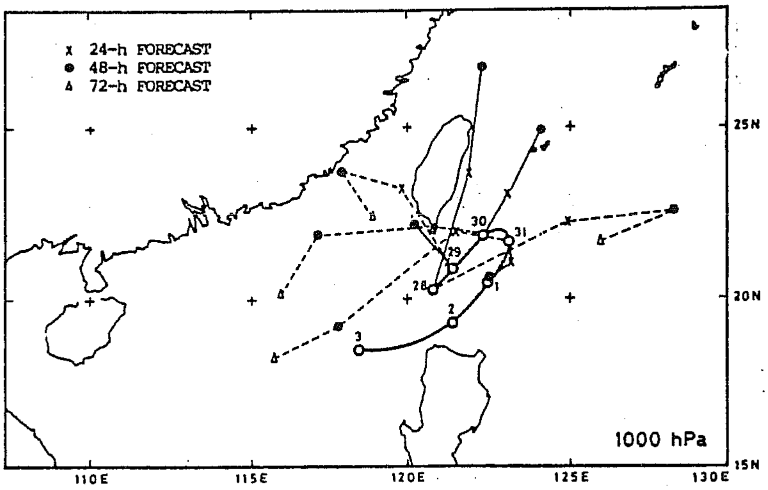

Fig. 2.11. As in Fig. 2.3 except for the period 2812-3112.

The quasi-stationary period of Wayne was not well predicted by the ECMWF model. Forecast tracks (Fig. 2.11) were rather inaccurate for the 2812 and 2912 time periods. Although the forecasts from 3012 and 3112 suggested an eventual southwestward displacement, the short-term forecasts showed a westward movement. As the flow around Wayne was quite weak between 2912 and 3112, these results are not particularly encouraging.

While the RO forecasts were mostly incorrect during this period, the turning of Wayne towards the southwest at 3112 was well predicted.

2.5. *Discussion*

Although this is a single case study, the results suggest that the ECMWF model predictions of TC movement can be useful at times. However, it is discouraging that the ECMWF model failed to predict two of the directional reversals. One situation involved the Fujiwhara interaction between Wayne and Vera. DeMaria and Chan (1984) have suggested that the radial vorticity distribution may be critical in determining the interaction between two TCs. Smith *et al.* (1990) also indicated that the structure of two TCs may be important in their mutual interaction. Therefore, the erroneous ECMWF forecasts during the period of Fujiwhara interaction could be due to an incorrect representation of the structures of the two cyclones. In another study, Morris (1989) suggested that the coarse resolution in the UKMO model is probably responsible for its failure to predict the motion of binary tropical cyclones.

The other group of inaccurate forecasts occurred during the period when the environmental flow was weak. With only weak steering currents, the beta-effect should dominate. The magnitude of this effect depends on the vorticity distribution of the cyclone (*e.g.,* Chan and Williams 1987; Fiorino and Elsberry 1989). Therefore, the poor forecasts in this period might be attributed to inadequate representations of the vortex in the ECMWF model.

The two other correctly-predicted directional reversals involved changes in the synoptic-scale flow. This implies that in situations in which the environmental flow is quite well-defined, the ECMWF model can provide a rather good forecast of the flow and hence the movement of the TC. Reed *et al.* (1988) also reached a similar conclusion based on the ECMWF predictions of the movement of tropical storms in the Atlantic.

The results from all these studies point to one fundamental problem in the global models in predicting the movement of TCs - the frequent inability of the model analysis to define a realistic TC circulation. If the synoptic-scale flow around the TC is well-defined, a large part of the motion of the TC is controlled by this flow which is usually well predicted by the global models. In this case, the TC structure becomes relatively unimportant. As a result, the ECMWF predictions can be quite good. On the other hand, in situations where the synoptic-scale flow is weak or another TC is in the vicinity, a misrepresentation of the TC structure will result in erroneous forecasts. Therefore, in order to improve the ability of a global model to predict TC tracks, it is imperative that the analysis contains a realistic cyclonic circulation.

Various operational centres have realized the problem of TC-structure representation in the analyses of the global or regional models. The different methods employed by the different centres will be described in the next section.

3. REPRESENTATION OF A TROPICAL CYCLONE IN THE MODEL ANALYSIS

A major reason why the circulation of a TC is usually not well represented in the model analysis is that TCs occur mostly over the ocean where observations are generally sparse. In the pre-satellite era, warnings on the locations of the TCs were sometimes quite inaccurate. As a result, ships could be caught in the vicinity of a TC and provided the much-needed observations to define the circulation of a TC. However, fewer such observations are now available because of better warnings to the ships. Therefore, the representation of a TC in the analysis of an operational NWP model has to rely almost exclusively on conventional rawindsonde data and satellite-derived winds and temperatures.

In general, the data assimilation schemes of most global models which utilize both the model forecasts and an objective analysis technique are usually capable of providing reasonable analyses of the large-scale flow in data-sparse areas. When the circulation of a TC does not extend beyond a few degrees latitude in radius, the peripheral data around the TC are not influenced by its circulation. As a result, the assimilation scheme cannot produce a good analysis of the circulation. In some cases, even if observations in the vicinity of a TC are available, quality control techniques in the analysis scheme may actually reject such data. This may occur because the first guess of the analysis (which is usually the short-term global model forecast) does not contain a circulation of the TC due to insufficient resolution or a deficient cumulus or radiation parameterization scheme. The analysis scheme is also generally not formulated for analyzing the TC circulation.

Several methods have been suggested to improve the model analysis to obtain an adequate representation of the circulation associated with a TC. The most obvious approach is to insert some bogus observations in the analysis. Alternatively, Puri and Lonnberg (1989) have suggested the use of high-resolution structure functions and modified quality control in the analysis of TCs. Using a different cumulus parameterization scheme, Heckley *et al.* (1987) were able to improve the ECMWF predictions of Hurricane Elena in the Gulf of Mexico. However, the TC in this case was in a relatively data-rich area. Whether the same scheme will improve the prediction of TC tracks in data-poor areas remains to be seen. Increasing the model resolution may be another option. Krishnamurti *et al.* (1989) have shown that a model with a T170 resolution produced much better predictions than the same model with only a T21 resolution. Again, their study concentrated on TCs during the FGGE year in which data were exceptionally abundant. Whether an increase in resolution alone (without a concomitant increase in data density) will enable a global model to make better TC track forecasts in general is still debatable.

All the operational centres have adopted the approach of inserting bogus observations. In the following sub-sections, the different schemes will be briefly described. Interested readers should consult the original articles.

3.1 UK Meteorological Office (UKMO)

The general characteristics of the UKMO global NWP model are described in Bell and Dickinson (1987). The horizontal resolution of the model in the tropics is around 200 km. Such a resolution is obviously inadequate in representing the detailed inner circulation of a TC (which, on the average, has a radius of maximum winds of < 50 km). During the analysis, human intervention in quality control of the data is often necessary.

According to Morris and Hall (1987), the strategy of the UKMO in the analysis of a TC has the following basic features:

(a) The objective is to correct the position of the circulation centre or to create a circulation only if none was present in the analysis.

(b) No attempt is made to model the detailed horizontal structure of a TC. However, a warm core is maintained in the vertical.

(c) The method is to insert bogus winds at four positions around the centre at each level between 850 and 500 hPa. The bogus winds are usually symmetric but could be made slightly stronger in the direction of movement of the TC if the translation speed is significant.

An example of the effect of bogussing is shown in Fig. 3.1. Using only routinely-available observations, the circulation of Typhoon Orchid was barely noticeable and its centre was in the wrong place (Fig. 3.1*a*). This is a rather typical analysis when few observations are available in the vicinity of a TC. After 12 bogus surface observations of mean sea-level pressure and winds as well as 12 bogus wind observations in the lower troposphere (four locations and three levels) were inserted, the resultant analysis provided a very good definition of the typhoon at 850 hPa (Fig. 3.1*b*). The 72-h forecasts from the two analyses show that the forecast positions of Orchid based on the one with the bogus observations are much closer to the observed positions (Figs. 3.1*c*, *d*).

Since 1986, the UKMO has been applying the above strategy in predicting TCs using its global model. The mean position errors of the analyzed/forecast positions of this model for TCs in the North Atlantic and the western North Pacific in 1986-87 are shown in Fig. 3.2. Notice the large mean initial position error of over 150 km compared with an average of 30-40 km made by forecasters in an operational forecast centre. The 24-h errors are also rather large[2]. However, at 48 hours and beyond, the model shows considerable skill in predicting the positions of TCs. Thus, it appears that the UKMO global model shows promise in the medium-range forecasting of tropical cyclone tracks when bogus observations are inserted.

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[2] Based on the reports by the Joint Typhoon Warning Center (JTWC) in Guam (JTWC, 1986, 1987), the 24-, 48- and 72-h JTWC position errors for these two years are around 210, 430 and 640 km respectively. The corresponding errors from a persistence-climatology type method are around 235, 480 and 740 km respectively.

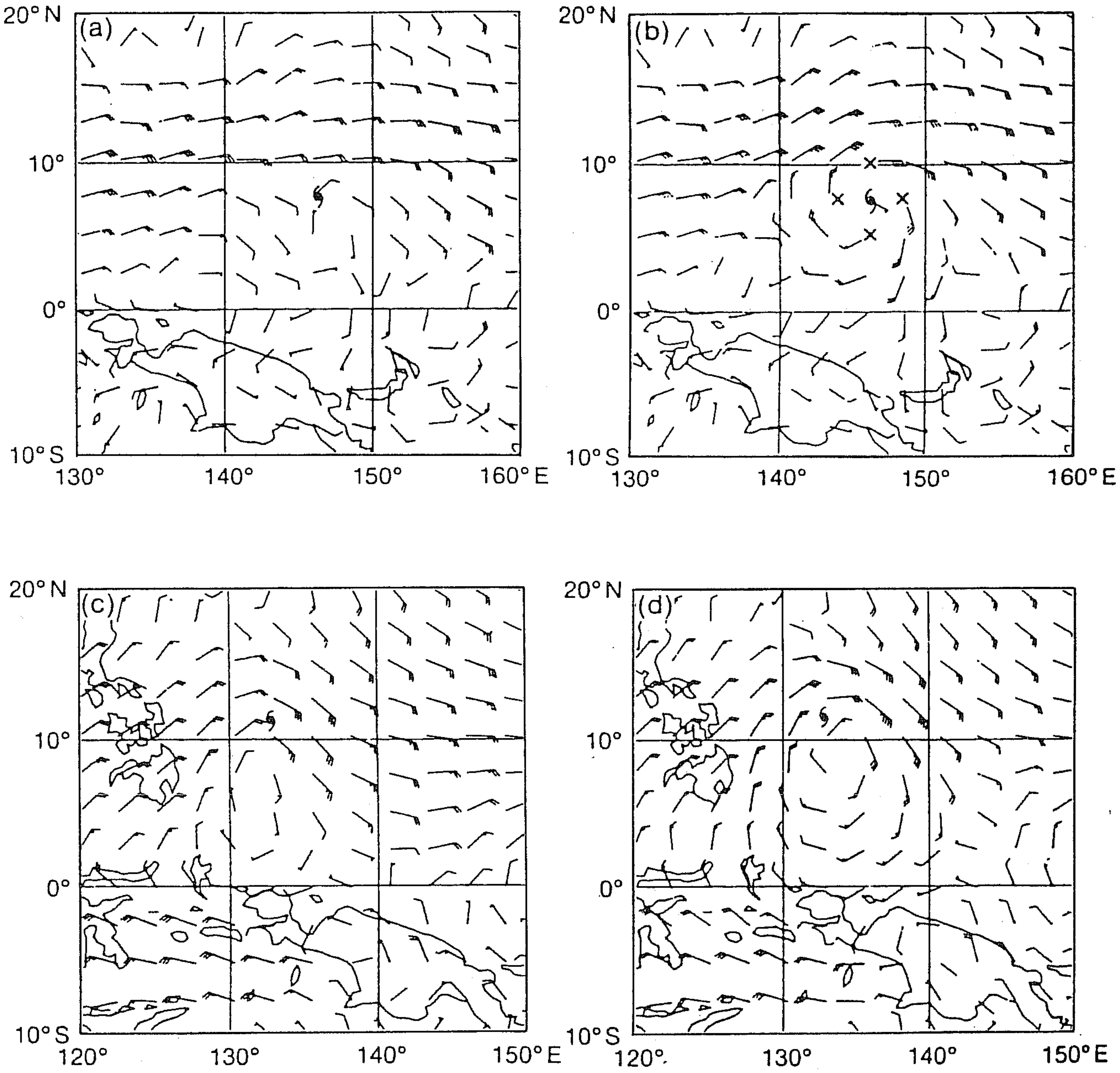

Fig. 3.1 UKMO global model 850 hPa wind analysis/forecast: (a) analysis for 1200 UTC on 9 January 1987; (b) as in (a) except with the inclusion of bogus observation at the locations marked by (x); (c) 72-h forecast valid at 1200 UTC on 12 January 1987 with no bogus observations included in the analysis; and (d) as in (c) except with the inclusion of bogus observations. The positions of Typhoon Orchid are shown by the tropical cyclone symbol *(from Morris and Hall, 1987)*.

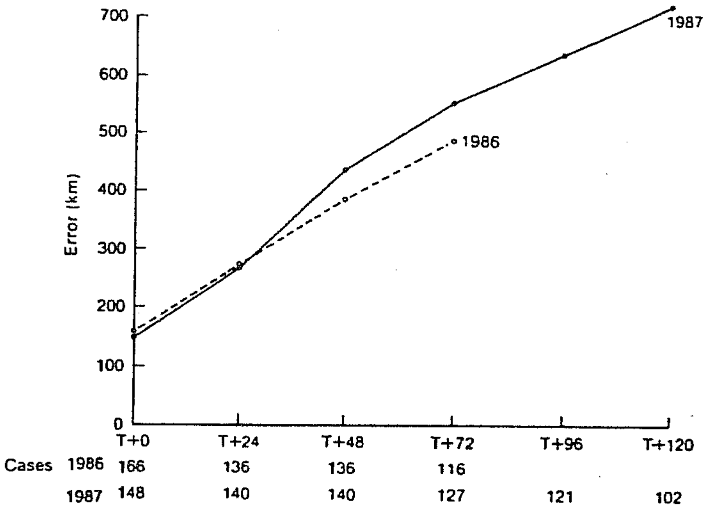

Fig. 3.2 Mean position errors of the UKMO analyzed/forecast positions of tropical cyclones in the North Atlantic and western North Pacific in 1986-87 using only 0000 UTC data and for TCs with maximum sustained winds ≥ 50 knots *(from Morris and Hall, 1987)*.

3.2 Japan Meteorological Agency (JMA)

The JMA has a typhoon model (TYM), an Asia model (ASM) and a global model (GSM) with resolutions of 50, 75 and 180 km respectively. Bogus data are inserted into the analysis-forecast cycle every 12 hours. Based on the position, size and intensity of the TC, an axisymmetric surface pressure field is built around the TC (Iwasaki *et al.*, 1987). D-values are also calculated for the upper troposphere to incorporate the anticyclonic flow. Temperature and wind fields are then computed from the cumulus parameterization scheme and momentum equations respectively. The movement of the TC is also added to the wind field in the TYM. In addition, large-scale values of sea-level pressure, temperature and moisture are blended into the computed TC circulation before insertion into the model.

Although the focus here is on global models, it is instructive to compare the forecasts from these three models. The forecasts for Typhoon Gordon (Fig. 3.3) show that the GSM has the worst performance, probably because of its relatively low resolution. On the other hand, the TYM seems to have the best forecasts. Notice also that even with bogussing, the analyzed position of the TC in the GSM is still displaced from the actual position. This example suggests that increasing the resolution of a model *(in addition to bogussing)* may provide an improvement in predicting the movement of a TC.

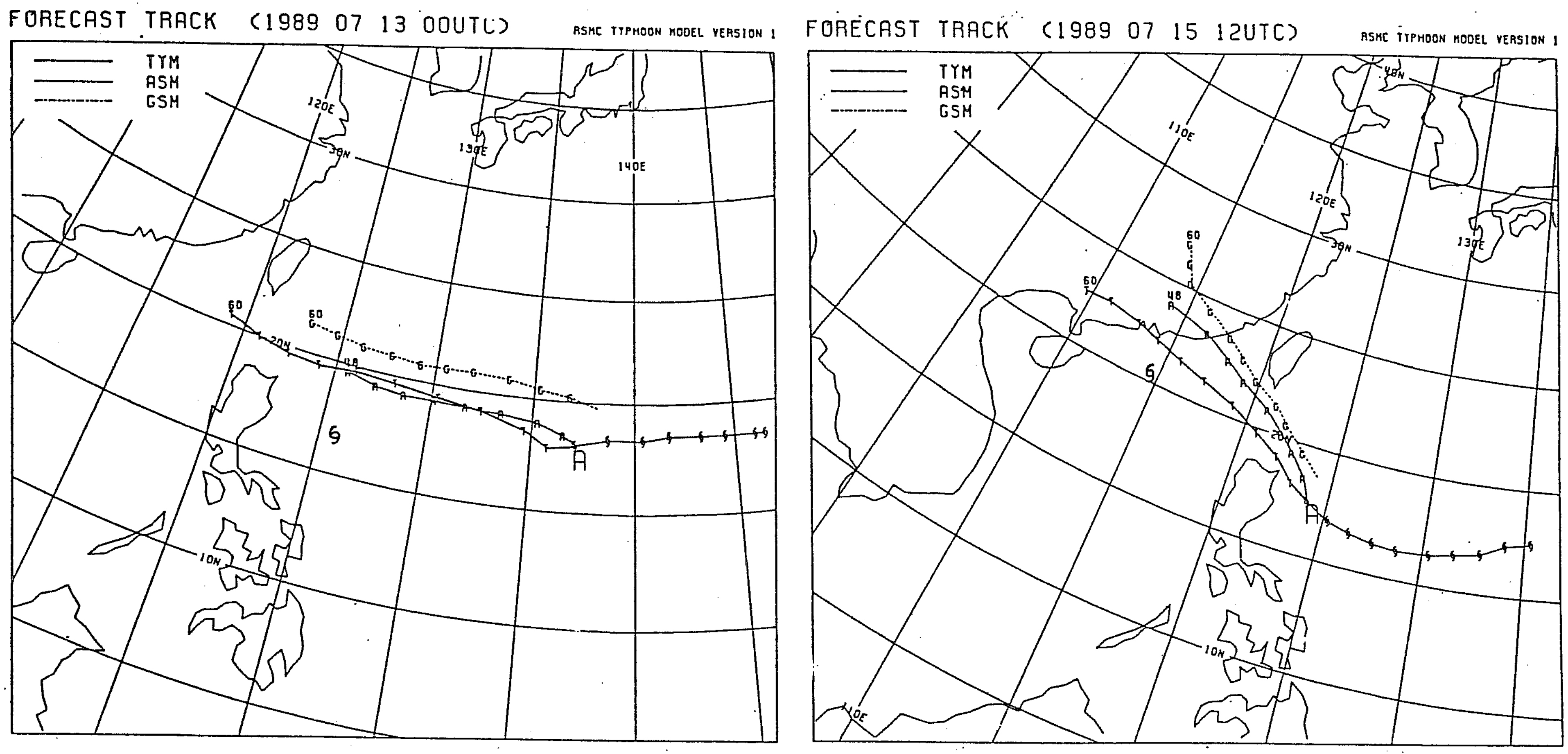

Fig. 3.3 Best track of tropical cyclone Gordon (solid line connecting tropical cyclone symbols) and the forecast tracks for two times (0000 UTC on 13 July 1989 and 1200 UTC on 15 July 1989) from the TYM (T connected by solid lines), ASM (A connected by solid lines) and GSM (G connected by dotted lines). The positions are plotted every 6 h *(from Kitade, 1989)*.

3.3 ECMWF

Currently, the operational ECMWF global model has a T106 horizontal resolution (corresponding to about 125 km). The model analysis does not contain any bogus observations for the purpose of predicting TCs. However, Andersson and Hollingsworth (1988) have performed some experiments to study the effects of bogussing in the prediction of TC movement by the ECMWF model. The bogus observations are generated from a combination of a symmetric vortex and a background field. Several requirements should be met during the bogussing procedure:

(a) The response of the data assimilation to the bogus observations should be the generation of a realistic TC-like vortex.

(b) The analyzed large-scale flow should not be adversely affected.

(c) The analyzed vortex should be balanced enough to be accepted by the initialization procedure. It should also have a reasonable movement and development through the first six hours of integration so that a good guess field can be provided to the next analysis.

A Rankine vortex (Milne-Thompson 1968) is specified as the symmetric vortex while the background field is chosen to be the most recent 6-h forecast truncated at T20. It is assumed that the T20 fields contains information only on the TC environment. The wind bogus is inserted between 850 and 300 hPa with weightings decreasing with pressure. At 100 kPa, bogus mass data are inserted.

The two case studies made by Andersson and Hollingsworth (1988) show different results. For a TC in the Gulf of Carpentaria in the Australian region, predictions using bogus observations only (that is, excluding any observations within a certain area of the TC) are virtually the same as those using only observed data. In this case, large amounts of data were available since this cyclone, Jason, occurred during the Australian Monsoon Experiment. In another case in the western North Pacific, bogus observations did improve the forecasts significantly.

3.4 Summary

The biggest problem in TC forecasting is that TCs spend most of their lifetime over open oceans where observations are usually sparse. Therefore, the *only* way to improve the analysis seems to be the insertion of bogus observations. The work of the various operational centres provides strong support for this assertion. Increasing the resolution of the model, using high-resolution structure functions or a different cumulus parameterization scheme can only complement but *not* replace the use of bogus data.

However, no consensus as to the best technique for TC bogussing has emerged. Whereas the UKMO inserts mostly wind data, the JMA boguses almost all atmospheric variables. The horizontal and vertical structures of the bogus vortices are also different. More experiments need to be performed to determine the optimum strategies for bogussing. This need is even stronger now in view of the results of recent theoretical and numerical studies on TC motion (*e.g.,* DeMaria 1985, 1987; Chan and Williams 1987; Fiorino and Elsberry 1989; Evans 1990; Smith *et al.* 1990; Shapiro and Ooyama 1990 *etc.*) which suggest the importance of the structure of a TC in controlling its movement due to its interaction with the environment.

4. PREDICTION OF TROPICAL CYCLONE FORMATION

So far, most of the operational centres have concentrated on the track forecasting aspects and studies of the ability of global models to predict the formation of TC-like vortices have been very few. Morris (1989) analyzed the UKMO model predictions of TCs in the South Indian Ocean and the South Pacific during the 1988-89 season and found that the model was able to develop strong cyclonic circulations in generally the right places. While false alarms did occur, these could at least be partly attributed to the lack of data in producing a "correct" analysis. In fact, Morris (1989) pointed out that the TC-like vortices did not develop in a random manner but formed in response to upper-level dynamical forcings. However, Andersson and Hollingsworth (1988) found the formation of a false tropical cyclone in one of their experiments for TC Jason using the ECMWF model.

With better cumulus and radiation parameterization schemes, global models should be able to develop TC-like vortices. Much more research is obviously needed in this area. An evaluation of the performance of the models may indicate the large-scale conditions in which the models are able to develop these vortices, and perhaps result in new insights of the physical processes in real TCs.

5. INTERACTION BETWEEN A TC AND A COLD SURGE - A CASE STUDY

During transition seasons, the south China coast can be affected by winter monsoon surges from the north as well as TCs from the east or south. When these two types of weather systems occur simultaneously, the forecasts can be rather difficult. For example, an intense winter monsoon surge in November 1987 brought temperatures along the south China coast down by > 15°C in 24 h. At the same time, Typhoon Nina was approaching the coast from the southwest. The coupling of the surge and the circulation associated with Nina caused winds over the coastal areas to reach gale force (> 17 m s^{-1}). In this section, the performance of both the ECMWF and UKMO global models in predicting the pressure and temperature changes over Hong Kong will be described.

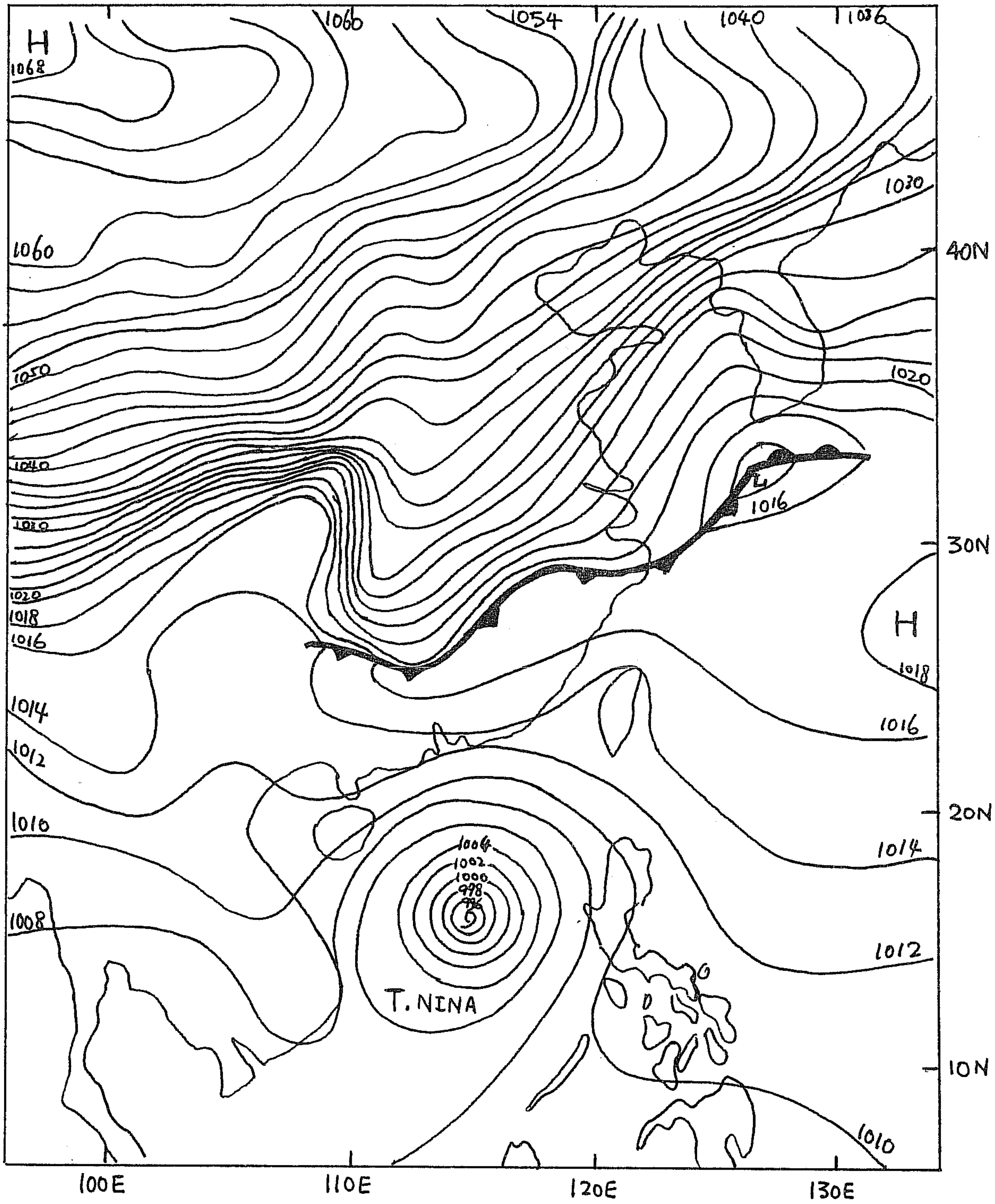

Fig. 5.1. Surface analysis at 0000 UTC on 27 November 1987.

5.1 *The synoptic background*

The synoptic situation about 24 h before the surge arrived at the south China coast is shown in Fig. 5.1. At this time (2700), the surface cold front associated with the winter monsoon surge was located at around 25-28°N. Temperatures were < 10°C behind the cold front and > 20°C ahead of it. Notice the weak pressure gradient over south China but slightly stronger gradient along coast due to the approach of Typhoon Nina, the track of which is shown in Fig. 5.2.

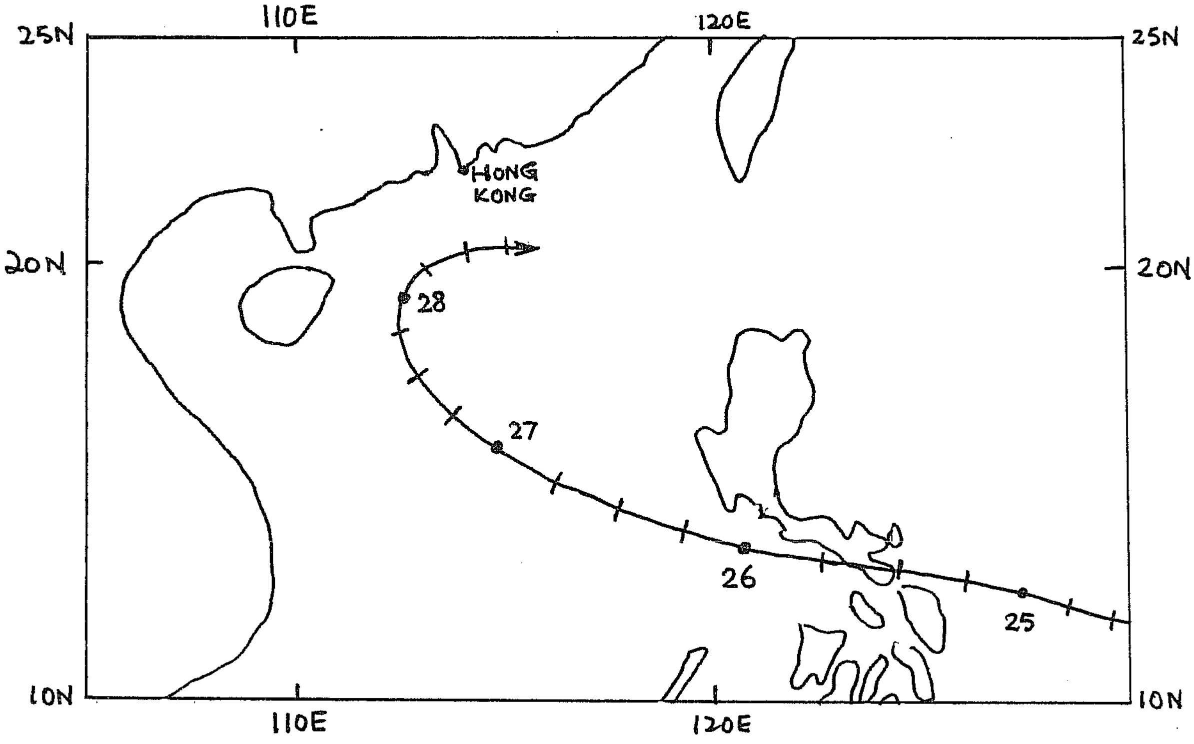

Fig. 5.2. Best-track of Typhoon Nina as derived from post-analysis by the Royal Observatory, Hong Kong. The dots along the track indicate the 0000 UTC positions on the day shown next to the dots. Lines along the track are intermediate 6-hourly positions.

The cold front moved southwards at a speed of around 5 m s^{-1} and passed through Hong Kong just before 2800. During this 24-h period, Nina turned northwards although the ECMWF and UKMO models predicted it to move southwestwards (not shown). As the cold front pushed further southwards, Nina rapidly weakened. The cold air was also modified significantly over the northern part of the South China Sea.

5.2 *Prediction of pressure changes*

The differences between the sea-level pressures over Hong Kong predicted by both global models (interpolated from the grid-point data) and those observed are shown in Fig. 5.3. Prior to the surge, the predictions were generally within 2 hPa of observed. However, near the time of arrival of the surge, both models predicted too high a surface pressure. The errors ranged from about 5 hPa for the 24-h forecasts to about 9 hPa for the 96-h forecasts. Then, after the passage of the cold front, both models under-predicted the surface pressure, although the ECMWF model appeared to have a smaller error.

The too high pressures in the model predictions near the arrival time of the surge could probably be attributed to the failure of both models in predicting the approach of Typhoon Nina towards the south China coast. With the demise of Nina, the large-scale dynamics apparently took over and the ECMWF performance was much improved. It is not clear why such large negative errors were present in the UKMO model predictions after the surge event.

5.3 *Prediction of temperature changes*

Operationally, forecasts of the 850-hPa (rather than the surface) temperatures are available from both models. Therefore, these are compared with the observed 850-hPa temperatures over Hong Kong (Fig. 5.4). As in the case of pressure predictions, the models did rather well prior to the surge, with errors of < 2°C. Near the arrival of the surge, both models predicted the 850-hPa temperatures to be too low, with the ECMWF model having the larger error. After the cold air had become established, the errors began to decrease.

The failure of the models in predicting the movement of Nina may again be the cause of these temperature forecast errors. Since the encroachment of Nina was not predicted by the models, warm advection associated with the circulation of Nina did not exist in the model prediction. Therefore, the temperature changes were solely due to the approach of the cold front so that the decrease in temperature was over-predicted.

5.4 *Summary*

The results of this case study illustrates the importance of having a model capable of forecasting the movement of TCs even when the primary interest is in other synoptic-scale weather systems which the global models should predict rather well. It appears, therefore, that the skill of the model can be reduced significantly if the interaction between tropical and extratropical systems is not properly represented in the model.

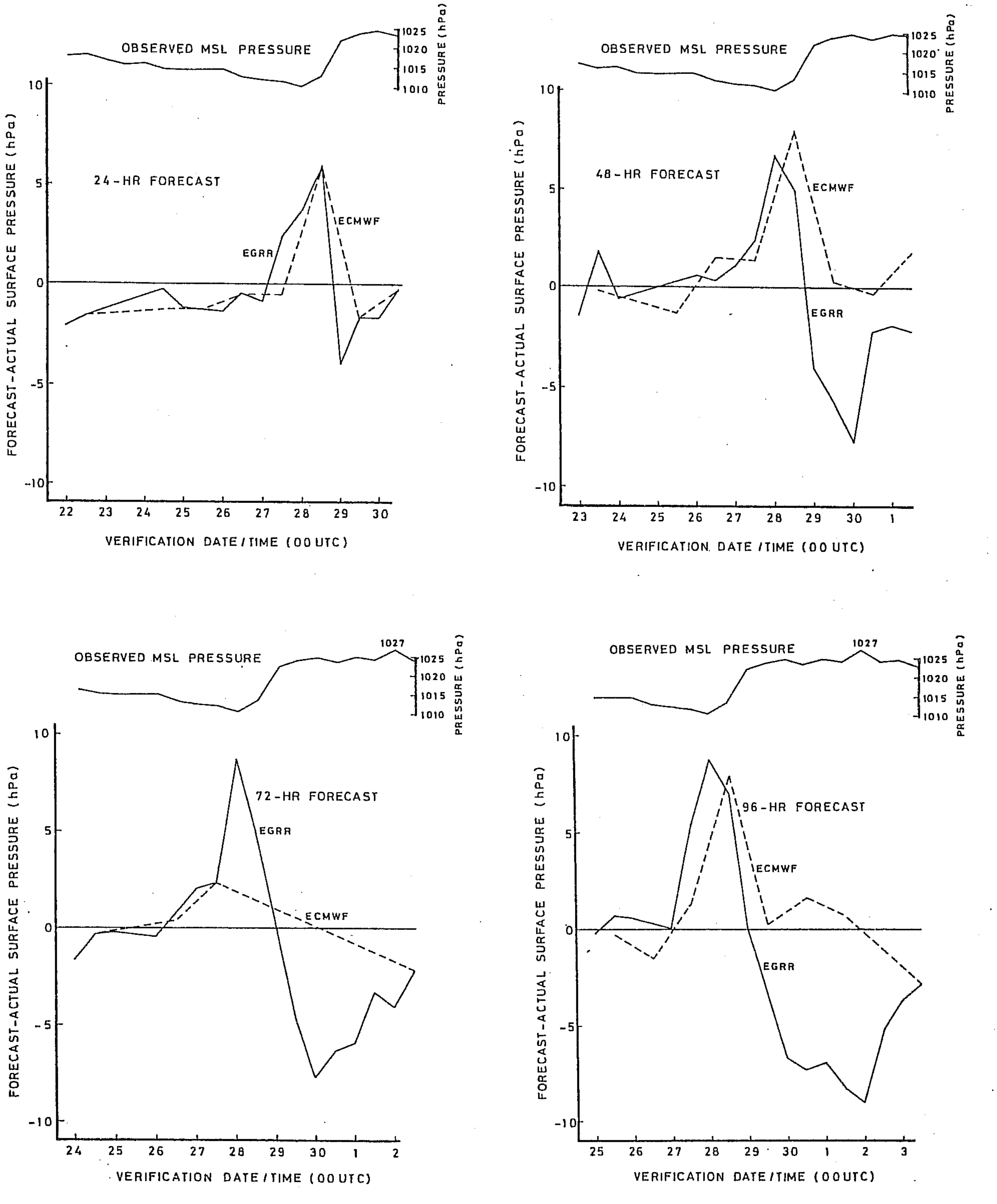

Fig. 5.3. Time variations of the differences between the forecast from the ECMWF and UKMO (EGRR) models and the actual observed sea-level pressures over Hong Kong (top of each figure).

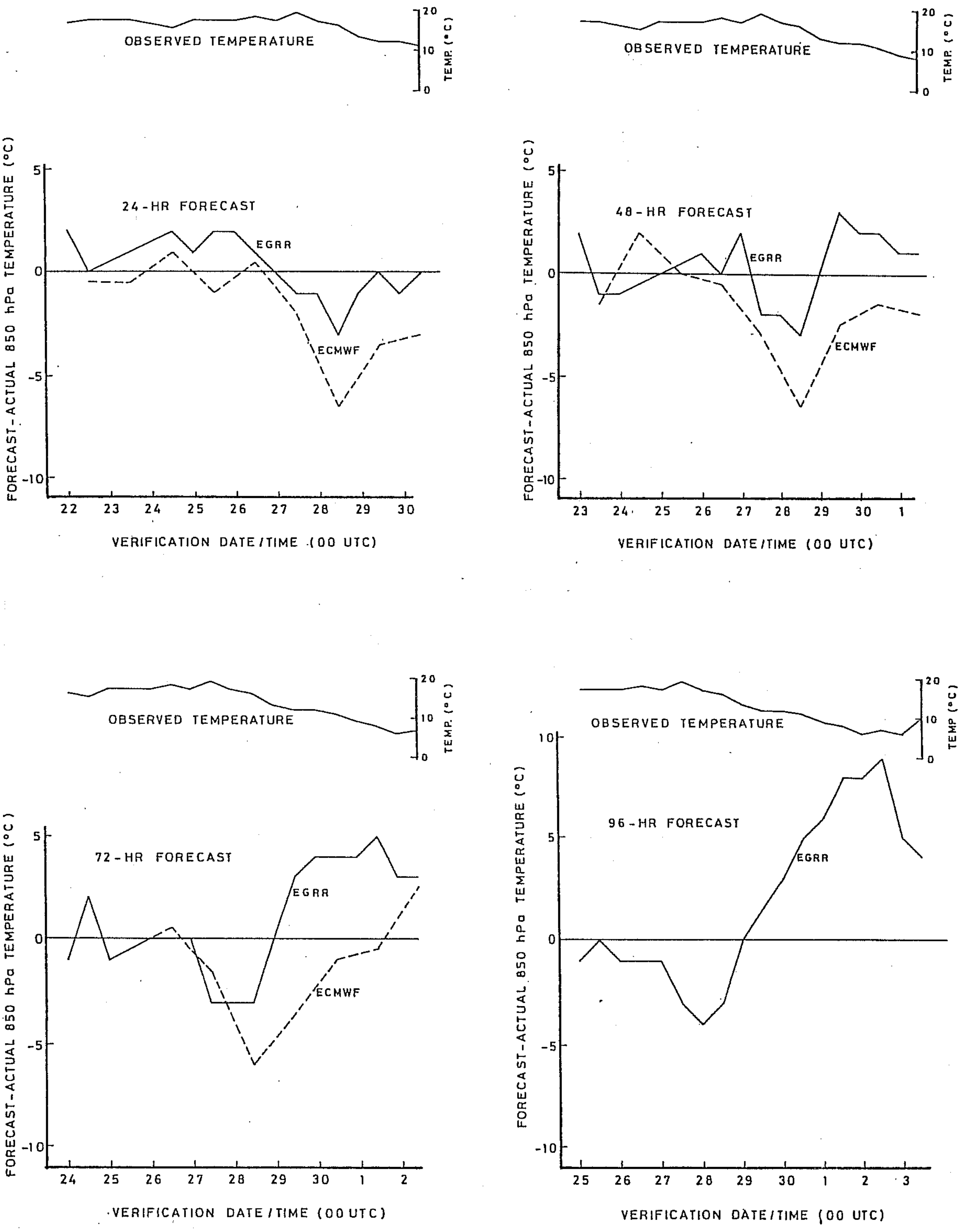

Fig. 5.4 As in Fig. 5.3 except for the 850-hPa temperature over Hong Kong.

6. CONCLUDING REMARKS

In this paper, the current status of global models in predicting one of the most important aspects of tropical forecasting - that of tropical cyclone formation and movement - is described. While it is comforting that some efforts are being put into improving the forecasting skill of global models in this aspect, much more needs to be done.

The first improvement should be in the representation of a TC circulation in the model analysis. New methods for designing and inserting a bogus vortex need to be identified. So far, most of the bogus vortices are symmetric. Recent theoretical and numerical studies (*e.g.,* Fiorino and Elsberry, 1989 and many others) have demonstrated the highly asymmetric nature of a TC circulation *even when the background flow is initially absent.* In an attempt to force a model vortex to move as the observed cyclone, Shewchuk and Elsberry (1978) superimposed wind vectors having the same direction and speed of the observed cyclone near the centre of the vortex in a limited-area model. This model has been one of the most successful TC-track forecast models used by the Joint Typhoon Warning Center in Guam (Tsui and Miller, 1988). Such a superposition essentially puts a wavenumber-one asymmetry into the model. Therefore, it seems that the insertion of an asymmetric TC structure into the analysis may help to simulate the actual circulation and thus lead to better forecasts.

The general philosophy in the operational centres in terms of bogussing is that the number of "artificial" observations should be kept to a minimum as they do not actually represent the conditions in the actual atmosphere. What is the minimum number of observations (both in the horizontal and vertical) that should be inserted to provide an adequate representation of the TC? Should the bogus vortex be chosen from a "menu" of pre-defined vortices or should it be different every time it is inserted into the analysis? Should dynamic as well as thermodynamic variables be included in the bogussing or should the analysis be allowed to estimate some of the variables through the data assimilation process? These are some of the questions that need to be addressed in future research in the bogussing problem.

Other alternatives for improving the analysis should also be explored. These include an increase in model resolution (which is happening in any case), sensitivity tests of the cumulus and/or radiation parameterization schemes, modified quality control to accept scarce-but-valuable data in the vicinity of a TC, etc. However, any claim of an improvement in the performance of the model in TC forecasting through the use of bogus observations and/or the inclusion of one or more of these alternatives must stand the test of time. That is, a large number of cases must be studied and statistical tests be made to evaluate the performance of the model under different conditions.

Such evaluations should be done for the operational version of the models as well. As demonstrated by Chan *et al.* (1987), analyzing the performance of a model will enable the identification of the strengths and weaknesses of the model. This will help the developers of the model to improve the model performance and let forecasters know when to accept the model forecast guidance.

More studies on the ability of global models to predict the formation and intensity changes of tropical cyclones should be carried out. Such studies will help operational forecasters make better medium-range weather predictions. Analyses of the conditions under which the model is successful in such prediction may lead to new insights into the physics of TC formation and intensity changes.

Although this paper is mainly concerned with tropical cyclone forecasting by global models, this does not mean that the model has high forecast skill for other tropical weather systems. The interaction between extratropical and tropical systems needs to be better simulated, as has been demonstrated in the case study presented in Section 5. Performance of the models in forecasting other tropical weather systems should also be evaluated. For example, Chan (1989) found that by improving the topography representation of a mountain ridge over south China in a limited-area model, better predictions of the southward migration of cold fronts and the anchoring of squall lines could be made. Thus, evaluations of the forecast skill must be actively pursued.

With the advances in computer and communication technologies, global models are now routinely used in tropical weather forecasting with reasonable success. However, the global centres should devote more efforts in improving the tropical forecasting skill. In addition, algorithms should be developed to determine the positions of tropical cyclones in the model prognoses. Such positions should be disseminated to forecast centres for operational forecasting and evaluation. Operational centres in the tropics using the global model products should also contribute by identifying the problems encountered during their routine forecasting. Information on tropical cyclones (such as position, intensity, size) should also be provided to the global centres in real time so that more realistic bogus observations can be inserted into the model. Through the cooperation between these two types of centres, it is hoped that in the not-too-distant future, tropical forecasting from global models can approach a skill level near that of the prediction of extratropical weather systems.

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REFERENCES

Andersson, E. and A. Hollingsworth, 1988: Typhoon bogus observations in the ECMWF data assimilation system. *ECMWF Tech. Memo. No. 148,* ECMWF, England, 25pp.

Bell, R. S. and A. Dickinson, 1987: The meteorological operational numerical weather prediction system. *Meteor. Office Sci. Pap. No. 41,* Meteor. Office, Bracknell, England.

Chan, J. C. L., B. J. Williams and R. L. Elsberry, 1987: Performance of the Nested Tropical Cyclone Model as a function of five storm-related parameters. *Mon. Wea. Rev.*, **115,** 1238-1252.

Chan, J. C. L. and R. T. Williams, 1987: Analytical and numerical studies of the beta-effect in tropical cyclone motion. Part I : Zero mean flow. *J. Atmos. Sci.*, **44,** 1257-1265.

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.

Chan, Y. K., 1989: The implementation and operation of an analysis scheme and a limited area model for Hong Kong. *Int'l Conf. on East Asia and western Pac. Meteor. and Climate.* P. Sham and C. P. Chang (Ed.), World Scientific Publish. Co. Ltd., Singapore, 429-438.

DeMaria, M., 1985: Tropical cyclone motion in a nondivergent barotropic model. *Mon. Wea. Rev.*, **113,** 1199-1210.

DeMaria, M., 1987: Tropical cyclone track prediction with a barotropic spectral model. *Mon. Wea. Rev.*, **115,** 2346-2357.

DeMaria, M. and J. C. L. Chan, 1984: Comments on "A numerical study of the interactions between two tropical cyclones". *Mon. Wea. Rev.*, **112,** 1643-1645.

Evans, J-L., 1990: A barotropic study of tropical cyclone motion. *Ph.D. Thesis,* Dept. of Math., Monash Univ., Australia, 170pp.

Fiorino, M. and R. L. Elsberry, 1989: Some aspects of vortex structure related to tropical cyclone motion. *J. Atmos. Sci.,* **46,** 975-990.

Heckley, W. A., M. J. Miller and A. K. Betts, 1987: An example of hurricane tracking and forecasting with a global analysis-forecasting system. *Bull. Amer. Meteor. Soc.,* **68,** 226-229.

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

Kitade, T., 1989: Advances in numerical modelling since IWTC-I. *Topic Chairman and Rapporteur Reports of the Second WMO International Workshop on Tropical Cyclones (IWTC-II).* World Meteor. Organ., Geneva, 1.0.1-1.0.10.

Krishnamurti, T. N., D. Oosterhof and N. Dignon, 1989: Hurricane prediction with a high resolution global model. *Mon. Wea. Rev.,* **117,** 631-639.

Milne-Thomson, L. M., 1968: *Theoretical hydrodynamics.* Macmillan Press, London, 743pp.

Morris, R. M., 1989: Forecasting the evolution of tropical storms over the South Indian Ocean and south Pacific during the 1988-89 season using the United Kingdom Meteorological Office operational global model. *Provisional Report to RA5*, World Meteorological Organization.

Morris, R. M. and C. D. Hall, 1987: Forecasting of the tracks of tropical cyclones with the UK operational global model. *ESCAP/WMO Typhoon Committee Annual Review 1987*, Typhoon Committee Secretariat, UNDP, P O Box 1864, Manila, Philippines, 102-105.

Puri, K. and P. Lonnberg, 1989: Use of high resolution structure functions and modified quality control in the analysis of tropical cyclones. *ECMWF Tech. Report* 65.

Reed, R. J., A. Hollingsworth, W. A. Heckley and F. Delsol, 1988: An evaluation of the performance of the ECMWF operational system in analyzing and forecasting easterly wave disturbances over Africa and the tropical Atlantic. *Mon. Wea. Rev.*, **116**, 824-865.

Shapiro, L. J. and K. Ooyama, 1990: Barotropic vortex evolution on a beta plane. *J. Atmos. Sci.*, **47**, 170-187.

Shewchuk, J. D. and R. L. Elsberry, 1978: Improvement of a baroclinic typhoon motion prediction system by adjustment of the initial wind field. *Mon. Wea. Rev.*, **106**, 713-718.

Smith, R. K., W. Ulrich and G. Dietachmayer, 1990: A numerical study of tropical cyclone motion using a barotropic model. I:The role of vortex asymmetries. *Quart. J. Roy. Meteor. Soc.*, **116**, 337-362.

Tsui, T. L. and R. J. Miller, 1988: Evaluation of western North Pacific tropical cyclone objective forecast aids. *Wea. Forecasting*, **3**, 76-85.