TECHNICAL MEMORANDUM

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Typhoon bogus observations in the ECMWF data assimilation system

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CONTENTS

ABSTRACT

The position and intensity of tropical cyclones are often known with high accuracy in near real time at the regional tropical weather centres, from non-conventional data types like satellite imagery and reconnaissance flights. In the context of the ECMWF data assimilation system a technique has been developed to improve the analysis of tropical cyclones in data void areas by incorporating this information in the analysis.

Input parameters such as position, maximum wind speed, radius of maximum wind and radius of gale-force wind, are used to create bogus observations which enter the analysis as if they were radiosonde observations. The bogus observations consist of two parts: (1) a symmetric vortex and (2) a filtered (low resolution) version of the background field; the two parts are superimposed. Winds are provided from 850 to 300 hPa, the strength decreasing with height, while geopotential is provided at 1000 hPa.

The bogus observations are designed to reflect conditions in the outer area of the storm. The intensity of the storm core cannot be resolved by the analysis scheme. The wind structure of the outer region is resolved by the analysis and it does not change quickly in time. Moreover, the outer wind structure is known to be very important for a good prediction of tropical storm motion.

The technique has been developed on tropical storm JASON of February 1987, an Australian Monsoon Experiment (AMEX) case. Tropical storm LYNN in the North Pacific of October 1987 was used for evaluation.

The effect of the bogus observations on the analysis is to correct the position of the storm and to make the wind structure of the outer region more realistic and better defined. The results from four consecutive forecasts of the LYNN-case show a substantial improvement in predicted speed and direction of the storm motion.

Similar techniques are already in operational use at other centres. We suggest that the necessary input data be acquired routinely at ECMWF, perhaps in cooperation with regional tropical weather centres.

1. INTRODUCTION

Tropical cyclones are often badly represented by the operational data assimilation system, even in their mature stage. The meteorological observation network is in many areas not dense enough to sufficiently measure tropical cyclones. Over much of the vast ocean areas where the storms develop they can be missed completely by the conventional observations globally available. The resolution of the analysis system is itself a limiting factor. The statistical structure functions used in the analysis do not acknowledge the existence of such intense small-scale features as tropical cyclones; the analysis can only represent the outer environment of a storm. The analysis is designed to reject data it cannot represent. Hence it rejects data on typhoon cores. That is one reason why the analysed tropical cyclones appear too large and weak. However, we do want to get the location of the centre right if we can. As shown by Reed et al. (1988) a good track forecast for a hurricane is possible if the initial position is accurate.

The most readily available data for the objective analysis of tropical cyclones are SATEMs and SATOBs and to lesser extent SYNOPs. SATEMs, temperature profiles retrieved from satellite measured radiances, are comparatively plentiful with a resolution of approximately 200 km, but in cloudy areas they are not very reliable; heavy precipitation, too, deteriorates the quality. Satellite cloud-track winds, SATOBs, sometimes occur in the cloud top levels of the storms and can be important to capture the outflow of the upper levels. Le Marshall et al.(1985) has shown that these two satellite data types are complementary and together they can improve the analysis of tropical cyclones.

PILOTs and TEMPs are usually the most reliable data, but they are widely separated in the tropics. Roughly 60 PILOTs and 50 TEMPs enter the analysis within the tropical belt at 00 and 12 UTC.

The effective resolution of the analysis is determined not only by the observation density; an upper bound is defined by the model grid, which is T106 L19 at present. The scale of the response to the observations is also determined by the statistical structure functions. The structure functions were recently revised by Lönnberg (RD Internal Memo, June 1988) and the new higher resolution version was implemented in July 1988. The new functions have a horizontal scale length at the equator of 600 km (compared to 1000 km previously) decreasing to 400 (500) km at 30 degrees north (south). With that modification, a considerable improvement of the tropical cyclone analysis is foreseen when there are enough good quality observations.

In the proceedings of the WMO international workshop on tropical cyclones, Bangkok 1985, a comprehensive review is made of current analysis and forecasting methods (WMO, 1986). One of the conclusions of the meeting was that the emphasis of future research work in this field should be on improving the prediction of tropical cyclone motion, which remains the most important aspect of tropical cyclone forecasting. Reed et al. (1988) have shown that the ECMWF model can make useful forecasts of tropical cyclone tracks provided the initial position is well-defined.

Satellite visible imaging can provide information not provided by other observations. In manual operational forecasting they provide the most useful information for pin-pointing the location of tropical cyclones and for estimating their intensity and size, (Dvorak, 1984). This information is however not available on the GTS (Global Telecommunication System) in a standardized form. It is distributed as a worded message - the 'Tropical Cyclone Bulletin'.

At JMA, the Japan Meteorological Agency, it has been found necessary to incorporate this type of additional information in the global analysis system in order to reduce the error in position and intensity of typhoons (Kanamitsu, 1985). From three input parameters, (1) central position, (2) central pressure and (3) diameter, idealized typhoon soundings are created based on the climatology of typhoons - so called typhoon bogus observations. To represent a large typhoon, JMA use 19 soundings, all within 450 km of the centre of the storm.

There is a need for the bogus observations to work in conjunction with the rather sparse observation network of the tropics. The bogus data should agree with real surface observations and hence support them in the automatic quality control and make rejections of good data less likely. We will not attempt to use bogus data if there are sufficient observations of the upper air wind field (two or more PILOTs or TEMPs) in the vicinity of the storm.

This paper describes a technique to create bogus observations for the ECMWF data assimilation system and evaluates its impact on analyses and forecasts. The purpose of introducing such a technique would be to improve the prediction of tropical cyclone tracks as well as to improve the analysis. The main data source for the bogus data would be satellite images, interpreted by the regional tropical weather centres. We would like to have a small number of parameters describing the size, intensity and wind distribution of the storms disseminated from the regional centres in real-time on the GTS.

After a short summary of techniques used at other centres for creation of bogus observations, there follows a detailed description of the procedure used experimentally at ECMWF. Sections 5 and 6 contain the results from two test cases: JASON in January 1987 and LYNN in October the same year. In the final section we make the case for a global exchange of additional tropical cyclone data.

2. TECHNIQUES FOR CREATION OF TYPHOON BOGUS OBSERVATIONS

There have been several attempts to use bogus observations in numerical weather prediction, especially for initialization of high resolution Limited Area Models for tropical cyclone forecasting. Knowing that the storm track is influenced by the outer storm environment the usual approach has been to superimpose an idealized vortex on a large scale analysis followed by a balancing initialization procedure.

At the US Naval Environmental Prediction Research Facility (NEPRF), in Monterey, California, Hodur (pers.comm., 1987) used the full model equations on a very fine grid to spin up a set of tropical cyclones of different intensities and latitudes from idealized initial states. The set of tropical cyclones was then stored and used as a data set from which bogus observations were extracted and blended with a background field before entering the analysis.

A different approach has been taken in experiments at NMC, the National Meteorological Centre, Washington, where Mathur (1986) proposed a scheme to use bogus observations in the high resolution hurricane model. From a prescribed pressure field, controlled by three input parameters (central pressure, maximum pressure and size of the storm), wind fields were calculated in gradient wind balance and with an ad hoc vertical shear. Potential temperature bogus data were found from the hydrostatic equation. The bogus data entered through the NMC's OI analysis on a 1.1 degree grid. Integrations were done on a grid spacing of 40 km. The intensity and the track were predicted well. Marks (1986), also at NMC, used a simple symmetric vortex to form the so called Pocket Hurricane Model used to generate bogus vortices for spinning up the NMC Moveable Fine Mesh, MFM, model. The bogus wind fields were blended with the MFM fields. In order to support the wind increments, geostrophic increments were then added to the MFM height fields. The reported result was a substantial improvement in predicted +12 hour motion, at the expense of degraded forecasts in the range from 36 to 72 hours.

The use of bogus data has long been advocated by the UKMO (United Kingdom Meteorological Office). Their technique is based on manual intervention and it has proven very useful in supporting the analysis of tropical cyclones (Hall 1987, Morris, pers.comm., 1988). Its routine use has led to an improvement of the forecast movement. Normally the forecaster provides four wind observations which are inserted no less than 300 km from the centre, at each level below 500 hPa, with equal strength.

Bogus observations have also been used in research to investigate the role of vortex structure on tropical cyclone motion. Fiorino and Elsberry (1986) used a barotropic model to show that the motion was mainly governed by the large scale flow surrounding the hurricane. The strength of the cyclone outside the 15 m/s radius proved to be more important than the winds near the centre of the cyclone. deMaria (1986) found that by changing the distribution of winds at distances greater than 100 km from the centre, large differences in predicted cyclone tracks and speeds were obtained. Speeds varied from 1 to 4 m/s and directions varied from NNW to SSW.

3. TROPICAL CYCLONES IN THE ECMWF MODEL

The capabilities of the ECMWF N48 grid point model to forecast hurricane-type of vorticies was first discussed by Bengtsson et al. (1982). Dell'Osso and Bengtsson (1985) compared the performance of the N48 global model with that of the ECMWF Limited Area Model at resolution N192. The prediction of motion and development of the hurricanes was much improved by the increased resolution. Quah and Cheang (1988) studied the ECMWF forecast products available on GTS as of October 1985 and found that the model overpredicts the westward propagation of tropical cyclones and that there is a tendency for the predicted storms to move equatorward over the West Pacific and the South China Sea region. They stated that this shortcoming may be due to the lack of observational data east of 120E.

Reed et al. (1988) found that the ECMWF forecasting model is capable of forecasting the easterly wave disturbances of the tropical Atlantic. Three of the studied waves developed to tropical cyclone intensity and their +48 hour position was forecast with some success. Predictions of intensity were less satisfactory. The very low resolution of the analysis system in the tropics and its constraint of non-divergent analysis increments were identified as important shortcomings of the analysis technique. Both these aspects of the analysis system have been changed since (Lönnberg, RD Internal Memo, June 1988, and Undén, RD Internal Memo, January 1988, respectively).

More recently, with the present T106 model, the JASON tropical storm event was thoroughly investigated by Puri (pers.comm., 1987). He showed that the analysis improved with the higher resolution structure functions but the automatic quality control had to be bypassed in order to avoid rejections of data near the centre of the storm. He also demonstrated the importance of forecast resolution and the large differences between forecasts run with different convection schemes (see also Illari, RD Internal Memo, June 1988).

4. GENERATION OF THE TYPHOON BOGUS OBSERVATIONS

The bogus observations of ECMWF are generated with a simple idealized tropical cyclone model which consists of two parts; (1) an idealized symmetric vortex and (2) a background field. The two parts are superimposed. The symmetric wind field at all levels is modelled by a 'Rankine Vortex', as described by Milne-Thomson (1968) and previously used by Holland (1983) and others, see section 4.3.

4.1 Some requirements for the technique

The concept of introducing typhoon bogus observations in the data assimilation system relies on the following requirements.

The overall structure of a mature tropical cyclone is assumed to be simple enough to be described by just a small number of parameters. We expect that these parameters can be provided, in real-time, by regional operational centres.

The response of the data assimilation to the bogus observations must be faithful enough to generate a realistic cyclone. If not, the resulting analysed cyclone will conflict with any real observations in the vicinity of the cyclone.

The analysed large scale flow in the vicinity of the cyclone must not be adversely affected through the large-scale components of the horizontal structure functions, the initialization or by the bogus data themself.

The analysed cyclone has to be balanced enough to be accepted by the initialization and to move and develop realistically during the first six hours of integration so as to provide a good first guess for the following analysis.

In the forecast, the inserted cyclone must be able to keep its realistic features and not disintegrate or transform into a larger scale system, which will ruin the forecast over a large area. The direction of motion of a tropical cyclone is very sensitive to the distribution of winds in the outer region, as well as to the size of the storm.

4.2 The large-scale component

Asymmetry in a tropical cyclone is assumed to arise from the addition of a large scale background field to the idealized vortex. In order to get a balanced background field we have chosen to use the most recent six hour forecast (the first guess field of the analysis) truncated at T20. The T20 fields are assumed to be so smooth that they do not contain any information on the cyclone itself, only on its environment.

The background wind field is added to the idealized vortex at the bogus observation points. For the 1000 mb geopotential, the background field is added to the difference between the geopotential at the bogus observation points of the idealized vortex and the average value of geopotential along the circular edge of the vortex. However, one must bear in mind that using the forecast fields when creating the bogus observations inevitably involves the problem of 'incest'; it introduces a correlation between first guess and observations which is not accounted for in the present OI formulation.

4.3 The idealized vortex

In a Rankine vortex (Milne-Thompson, 1968), the tangential wind velocity (v) as a function of radial distance (r) is given by

$$v = v_m \left(\frac{r}{r_m}\right) \qquad r < r_m$$

$$v = v_m \left(\frac{r}{r_m}\right)^{-\alpha} \qquad r > r_m$$

where v_m is maximum tangential wind speed and r_m the radius of maximum wind speed. α is a parameter with value normally between 0.5 and 1. The gradient wind assumption is used to relate wind to geopotential (ϕ),

$$\frac{\partial\phi}{\partial r} = fv + \frac{v^2}{r} .$$

Applied to the inner region,

$$\frac{\partial\phi}{\partial r} = f\, v_m \frac{r}{r_m} + v_m^2 \frac{r}{r_m{}^2}$$

$$\phi(r) = \frac{v_m}{2} (f\, r_m + v_m) \left(\frac{r}{r_m}\right)^2 + C_1$$

Defining $\phi(0) = \phi_c$ = geopotential at the centre of the typhoon, gives

$$C_1 = \phi_c .$$

For the outer region,

$$\frac{\partial\phi}{\partial r} = f\, v_m \left(\frac{r}{r_m}\right)^{-\alpha} + \frac{v_m{}^2}{r} \left(\frac{r}{r_m}\right)^{-2\alpha}$$

$$\phi(r) = \frac{f\, r_m v_m}{1 - \alpha} \left(\frac{r}{r_m}\right)^{1-\alpha} + \frac{v_m{}^2}{(-2\alpha)} \left(\frac{r}{r_m}\right)^{-2\alpha} + C_2$$

Assuming 'undisturbed conditions' at some distance r_u = size of typhoon,

$$\phi(r_u) = \phi_u$$

gives

$$C_2 = \phi_u - \frac{f\, r_m v_m}{1-\alpha} \left(\frac{r_u}{r_m}\right)^{1-\alpha} - \frac{v_m^{\,2}}{(-2\alpha)} \left(\frac{r_u}{r_m}\right)^{-2\alpha}$$

Using the condition that the geopotential is continuous at $r = r_m$ we arrive at an expression for the geopotential at the centre of the typhoon (ϕ_c).

$$\phi_c = \frac{f\, r_m v_m}{2} \left(\frac{1+\alpha}{1-\alpha}\right) - v_m^2 \frac{\alpha+1}{2\alpha} + C_2$$

In summary, the mass distribution is expressed as a function of v_m, r_m, α, ϕ_u and latitude. α can either be set to a typical value of 0.6 or it can be derived from an additional input parameter, as for example radius of gale-force wind.

4.4 Vertical structure

The strength of the vortex is decreased with increasing height by a factor (W_i,i=1,N), where N is the number of levels. Values of W_i were taken ad hoc, with support from rawinsonde composites by McBride (1981). The composites indicate an almost constant wind speed from 850 to 500 hPa with a rapid decrease above, see Table 1 for our values. However, the case-to-case variation of wind strength with height within a tropical cyclone is complex and depends, amongst other things, on thermal stability and stage of development. No attempt has here been made to model this variability.

4.5 The bogus - horizontal and vertical distribution

Wind bogus is provided between 850 and 300 hPa while mass bogus is provided at 1000 hPa. We rely on the model physics to generate a consistent boundary layer and to set up the upper tropospheric outflow needed to keep the cyclone alive. We do not insert any humidity or thickness bogus data in order not to upset the convection. The wind bogus is in approximate gradient wind balance with the 1000 hPa geopotential bogus and it is left to the initialization to do the necessary balance adjustments to the upper air massfield. A table of bogus data variables, levels and the factor W is given below.

Level	1000	850	700	500	400	300
Geopotential	X					
Wind		X	X	X	X	X
Factor (W)	1.00	1.00	0.95	0.85	0.65	0.35

Table 1. The letter 'X' indicates a bogus data variable and the factor W is the reduction of vortex strength with height.

The horizontal distribution of the bogus observations can be seen in Fig.1. They are located along concentric circles, the circles separated by 130 km (the distance between latitudes of the grid) in the experiments described below. One observation is positioned at the centre. In the surrounding circles there are 4, 6, 8 and 10 observations respectively, to give a total of 29 bogus observations within a 600 km radius.

The bogus observations enter the analysis as if they were radiosonde observations, i.e. the same observation error is used for the two data types. However, the bogus observations will not be subject to any quality control within the analysis.

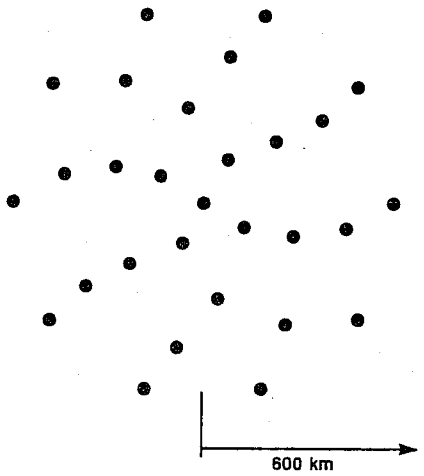

Fig.1 Horizontal distribution of the bogus observations.

4.6 Discussion

The information necessary to generate the bogus is already available at the regional tropical weather centres, but does not arrive at ECMWF in a suitable form. It does not always contain data about the winds away from the centre and its format is not automatically decodeable. For an automated system like the ECMWF's there is always the problem of controlling the quality of the incoming data. The insertion of bogus data perhaps has to be restricted to times when its input has been surveyed by staff.

The technique above is designed in concordance with the resolution of the global data assimilation system. Real observations that reflect structures on a smaller scale will conflict also with the bogus data and they will most likely be rejected.

A secondary effect of the bogus observations is that they reduce the estimated analysis error; the estimated forecast error is thereby decreased which will, in the following analysis, increase the weight given to the first guess field relative to the weight given to any ordinary observations that occur in the vicinity of the tropical cyclone. We will therefore avoid using bogus data when enough real observations are available.

5. THE JASON CASE

The JASON typhoon event occurred during the Australian Monsoon EXperiment, AMEX, and was therefore unusually well observed by PILOTs and TEMPs and is well documented. The three days 8-11 February 1987 served as the test-period over which our technique was developed. In the same period there was another tropical cyclone, CLOTHILDA, developing in the Indian Ocean east of Madagascar. Bogus data were provided for that storm too, and it was used in the evaluation of the technique.

5.1 Analyses

The high resolution structure functions were used throughout. At 14 degrees latitude the horizontal length scale of the functions is about 520 km. It means that the largest impact on the height field from a single wind observation is at 520 km distance perpendicularly to the wind direction either side of the wind observation. In a tropical cyclone the distance from the highest wind speed to the lowest pressure is typically between 30 and 80 km. Hence, even the higher resolution structure functions are an order of magnitude larger in scale than a typhoon. The problem is illustrated by Fig.2 which shows the analysis response to the bogus wind and pressure data, and the effect of the initialization. The curves show the first cycle of a data assimilation run, i.e. it is the first analysis in which bogus data have been inserted. The bogus observations are indicated as dots and the resulting analysis (thick line) is very smooth. The initialization mainly adjusts the massfield towards gradient wind balance which makes the cyclone deeper.

Given that the analysis tends to be too smooth, one may ask if the forecast model is able to deepen the cyclone, to make it better defined and give it a more realistic structure in a data assimilation run that has used the bogus data. From an assimilation with all the AMEX data plus bogus observations between 0 and 400 km radius, it was found that the band of maximum wind speed gradually moved closer to the centre of the cyclone, but still not closer than 250 km. The central pressure dropped slightly in the course of the integration and was 999 hPa in the final analysis (at 870211 12 UTC), (see Fig. 3a for the 850 hPa wind field). The bogus value was 994 but the 'best track estimate' was as low as 990 at that time.

The operational analysis is shown in Fig. 3b. The intensity was rather poor in spite of the unusually good data coverage. The circulation in the lower levels was weak and the lowest analysed pressure was 1003 displaced by about 350 km to the west. Some of the more important observations had been rejected by the quality control. The higher resolution structure functions were not used at that time.

In an assimilation run totally without ordinary observations within a 20 degree square around the typhoon and using the bogus data only within 400 km of the centre, an important interaction between the bogus wind observations and the analysis structure functions became apparent (see Fig. 4a). The large observation minus first guess increments close to the centre of the typhoon created unrealistic analysis increments at distances between 400 and 800 km from the typhoon centre. Over the warm ocean to the east of JASON it seems to have excited a false typhoon of the normal size and intensity of a 'T106 model typhoon'. To overcome this problem, either bogus winds have to be supplied up to much larger distances, past the negative lobes of the structure functions e.g. 600 km, or one must reduce the intensity of the bogus winds close to the centre of the typhoon.

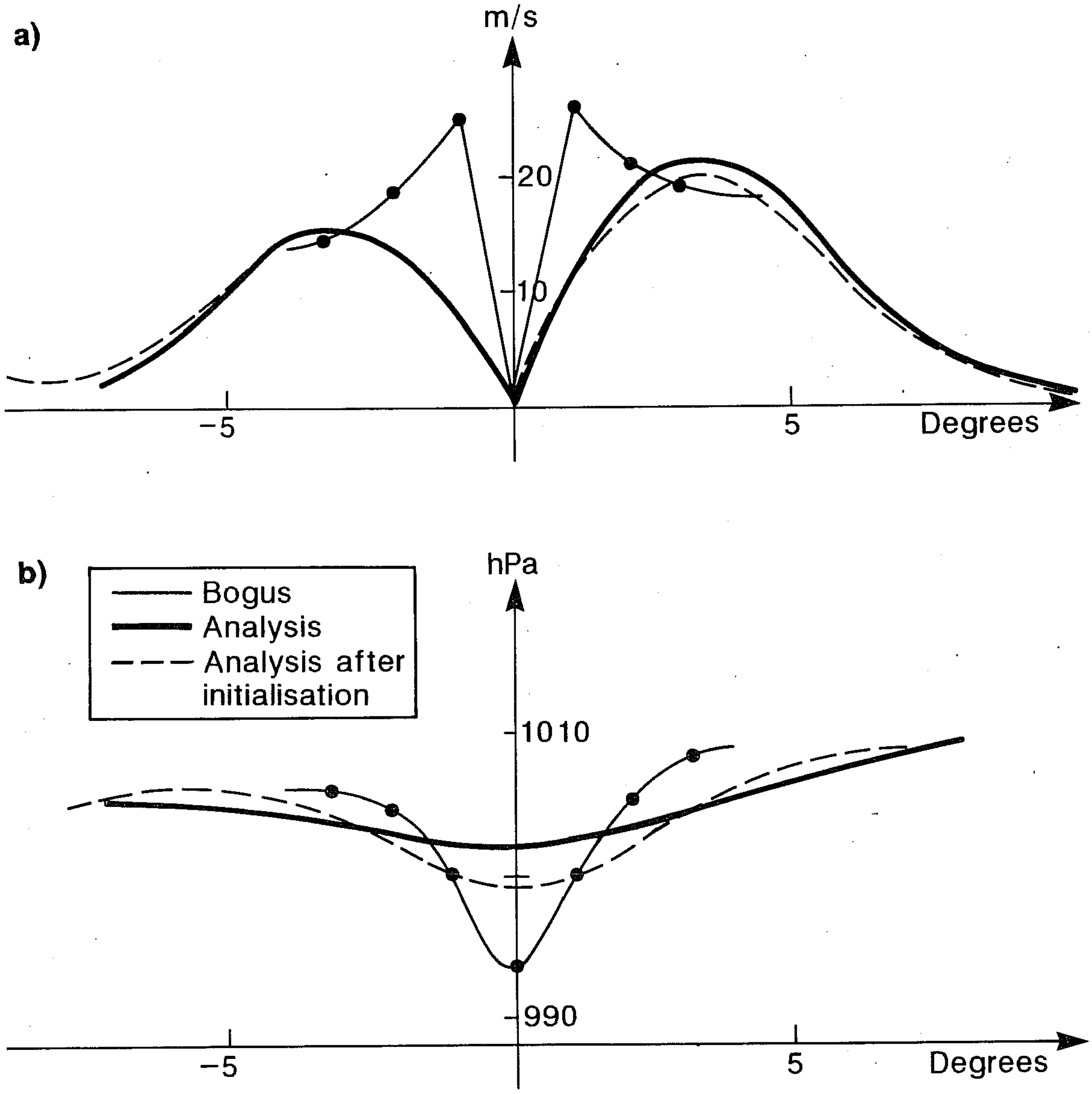

Fig.2 The response of the analysis and initialization to the typhoon bogus observations along 14S for the JASON case, a: 850 hPa tangential wind speed in m/s and b: sea level pressure in hPa. Abscissa is west-east distance in degrees of latitude. The dots indicate bogus observations which were provided as input to the analysis (thick line). Initialized analysis is shown as a broken line.

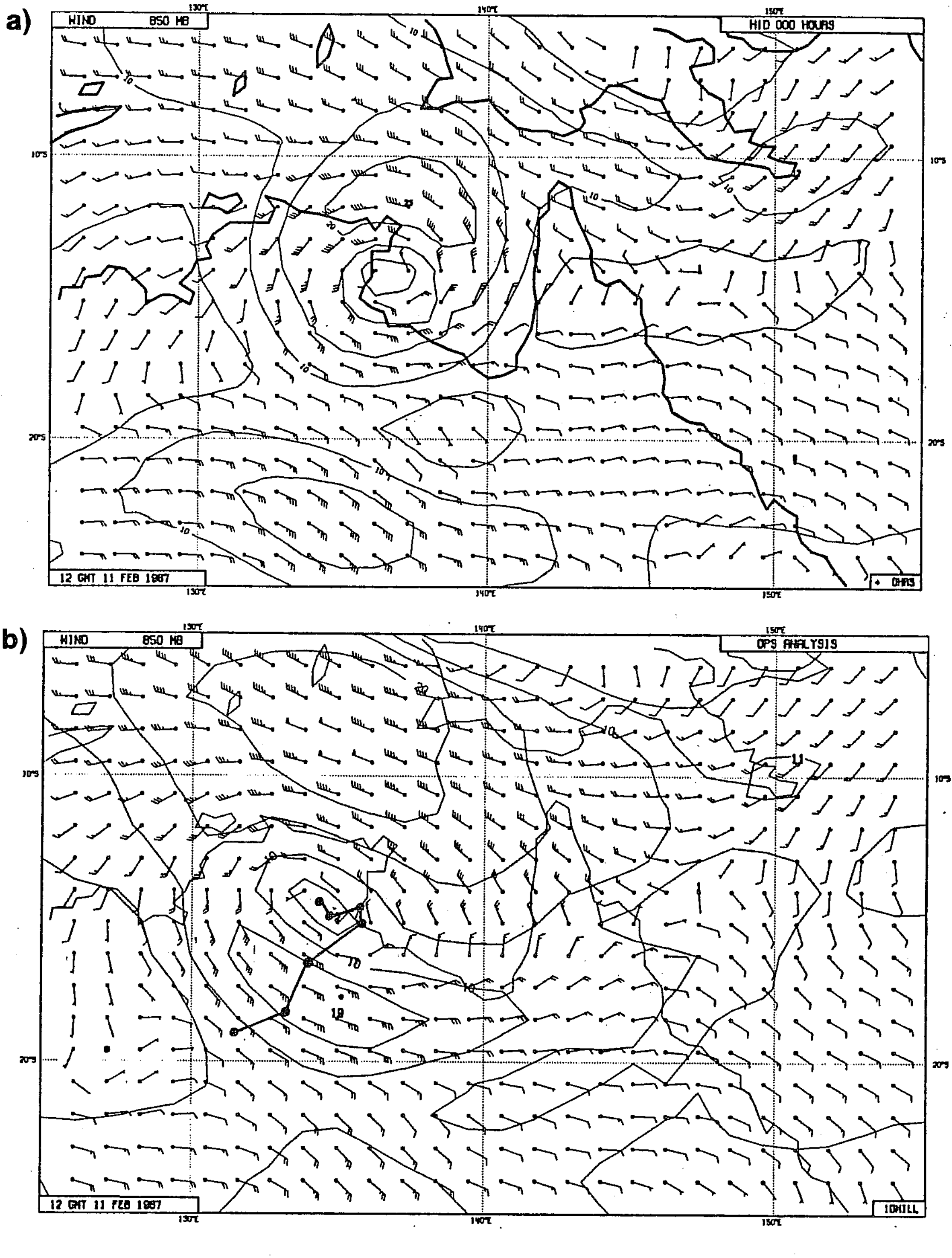

Fig.3 850 hPa analysed wind, 870211-12 UTC, tropical cyclone JASON, a: AMEX and bogus observations used and b: operational analysis together with operational 3-day predicted trajectory of storm motion. Windspeeds in m/s and 12 hours between dots along the trajectory.

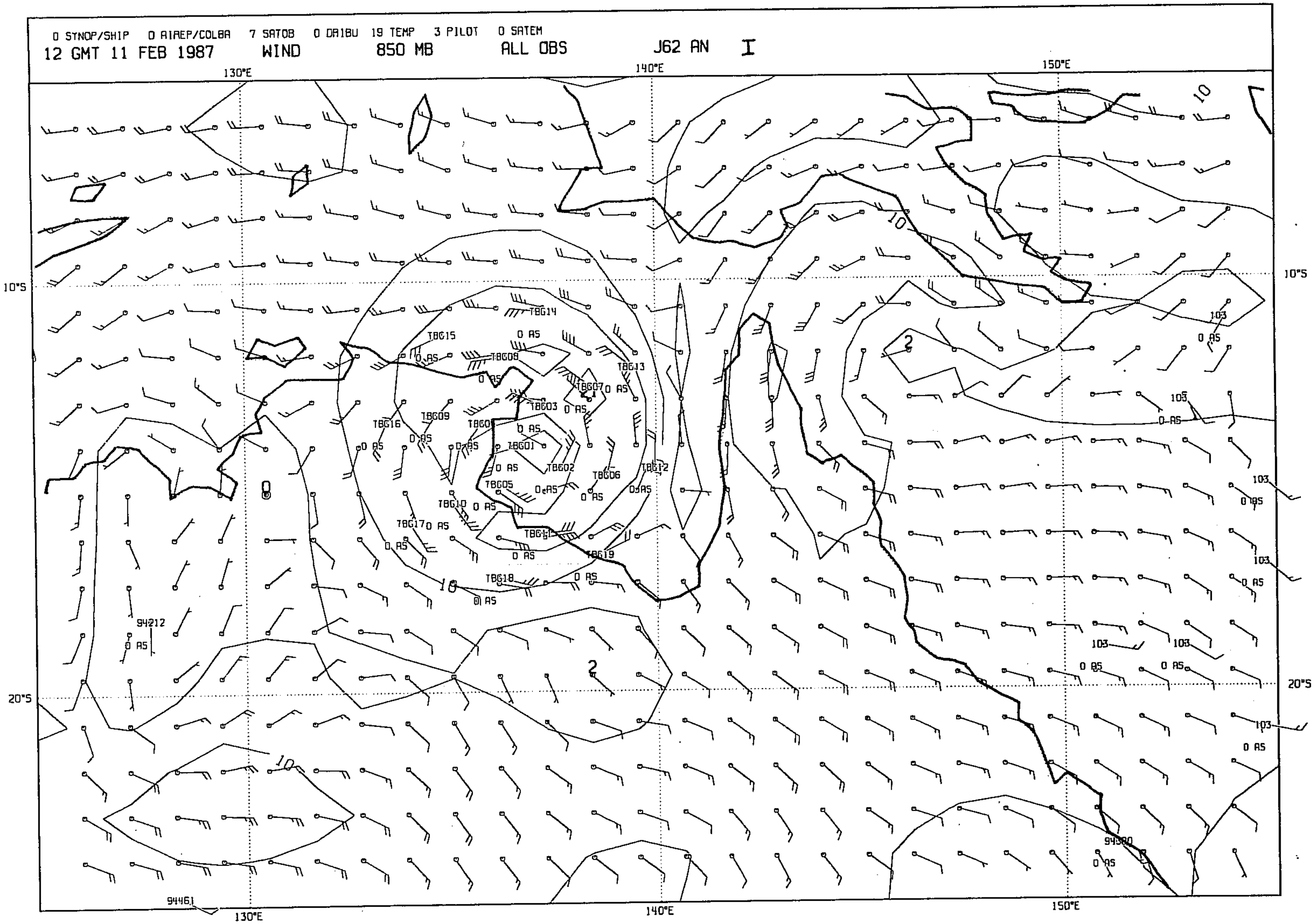

Fig.4a 850 hPa analysed wind and observations , 870211-12 UTC, tropical cyclone JASON. Windspeeds in m/s. No data except bogus observations in a 20 by 20 degree square around the tropical cyclone. Bogus observations to a radius of 400 km.

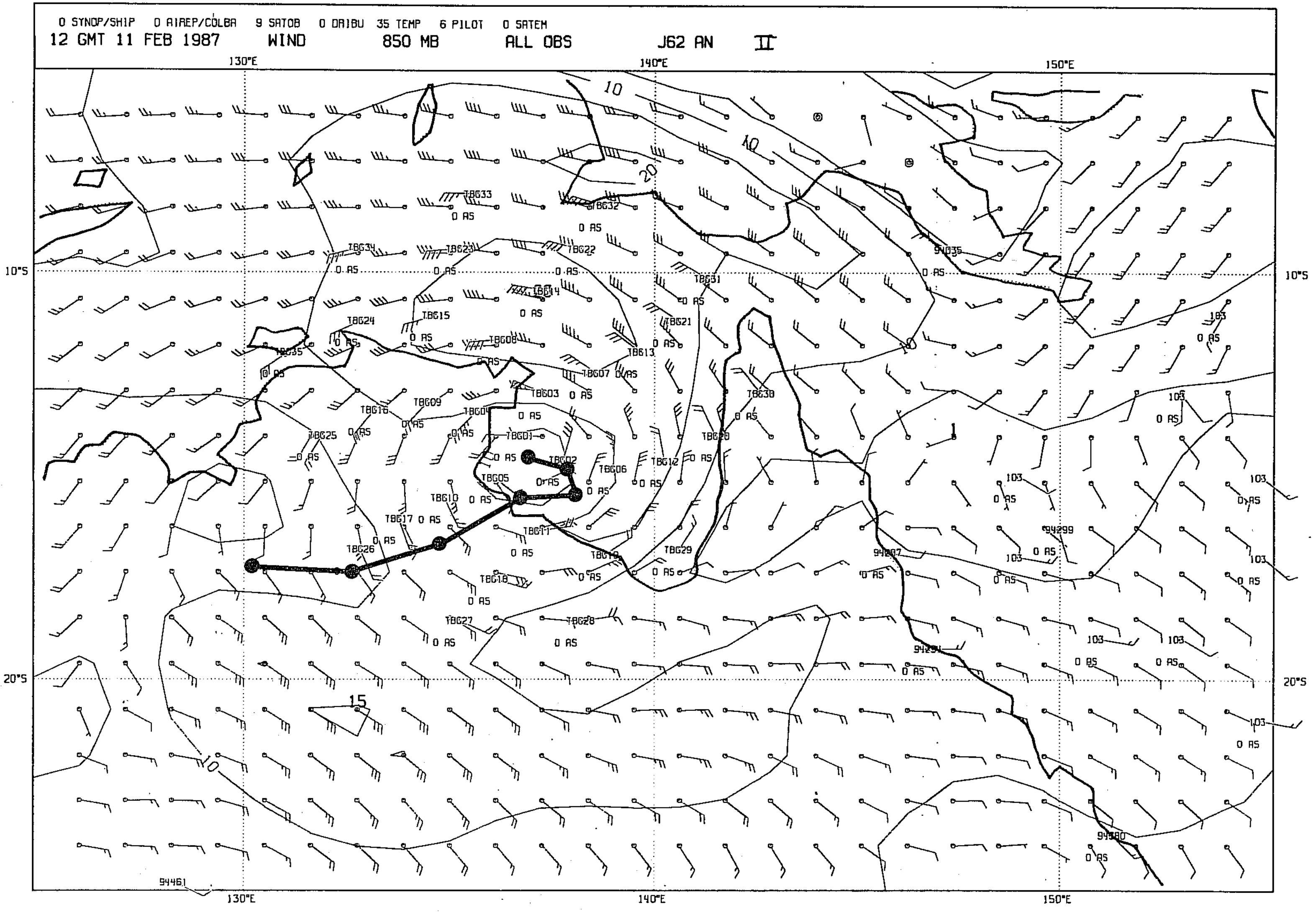

Fig.4b As Fig. 4a but bogus observations provided to a radius of 600 km. There is also a 3-day predicted trajecory of storm motion with 12 hours between dots along the trajectory

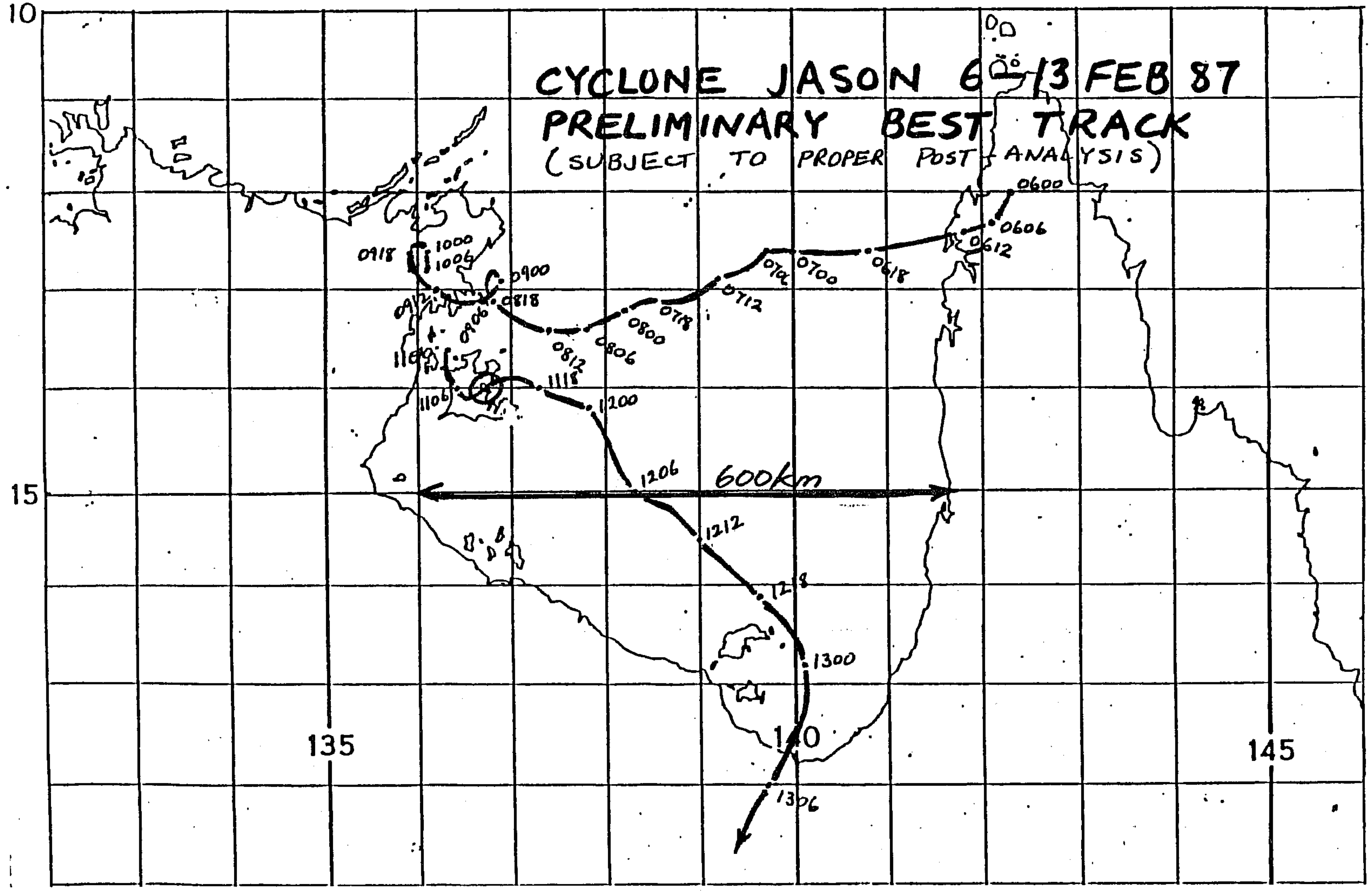

Fig.5 Estimated best track of tropical cyclone JASON.

Rerunning the experiment with bogus wind observations of unaltered intensity but to the distance of 600 km virtually solved the problem. The experimental analysis for the 11'th at 12 UTC can be seen in Fig.4b.

5.2 Forecasts

With the current resolution, the forecast model is incapable of producing a realistic tropical cyclone structure. Nothing of the inner structure nor the characteristic spiraling rainfall pattern can be found. The rapid fall in central pressure that occurs in developing typhoons is also too local a phenomenon to be simulated by the forecast model. Our attention when verifying is therefore focused on predicted storm motion.

The best track estimate is shown in Fig. 5. The trajectories for the forecasts with all the data (the operational) and for the forecast with the bogus only are shown in Figs. 3b and 4b respectively. Comparing the operational forecast with the forecast from the analysis using only bogus data within 20 degrees of the storm we see that the bogus-only analysis produces virtually the same forecast as the one that has used all the data. The direction of motion is correct for 24 hours but soon it goes straight back towards the west. The forecast errors appear to be mainly due to the Kuo convection scheme (K. Puri, pers.comm., 1987) rather than to the use of the bogus data instead of the real data.

6. THE LYNN CASE

The tropical cyclone LYNN formed in the central Pacific near the Marshall Islands and moved rapidly towards the Philippines along the southern periphery of the subtropical anticyclone. As it developed it decelerated and grew to a considerable size and intensity. On 19 October 1987 at 18 UTC it reached 'super typhoon' intensity (130kt) and maximum sustained surface winds were estimated to 72 m/s (140kt) shortly afterwards. The cyclone developed and moved mainly over data void ocean areas except for a few SYNOP/SHIP observations on or near the Mariana Islands and the radiosonde station on Guam which it passed 140 km to the northeast of at 12 UTC on the 18th. SATEMs were available through the developing stages of the cyclone but as it had matured there were no SATEMs any more for two and a half days. Gaps in the satellite coverage just at the position of the typhoon imply that the NESDIS retrieval procedure has succeeded in identifying and rejecting the radiances strongly contaminated by rain drops.

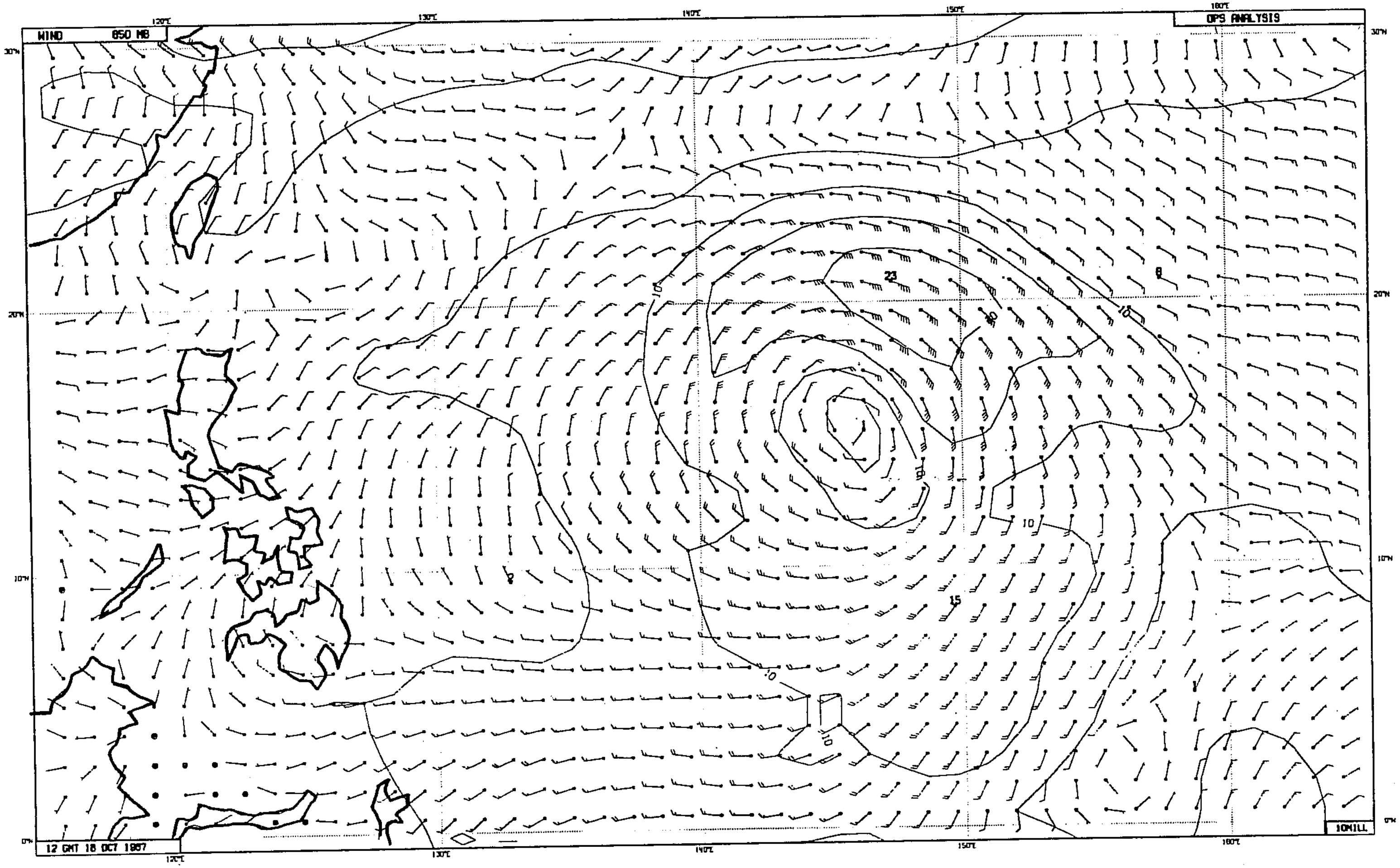

Fig.6a 850 hPa analysed wind, 871018-12 UTC, tropical cyclone LYNN, operational analysis. Windspeeds in m/s.

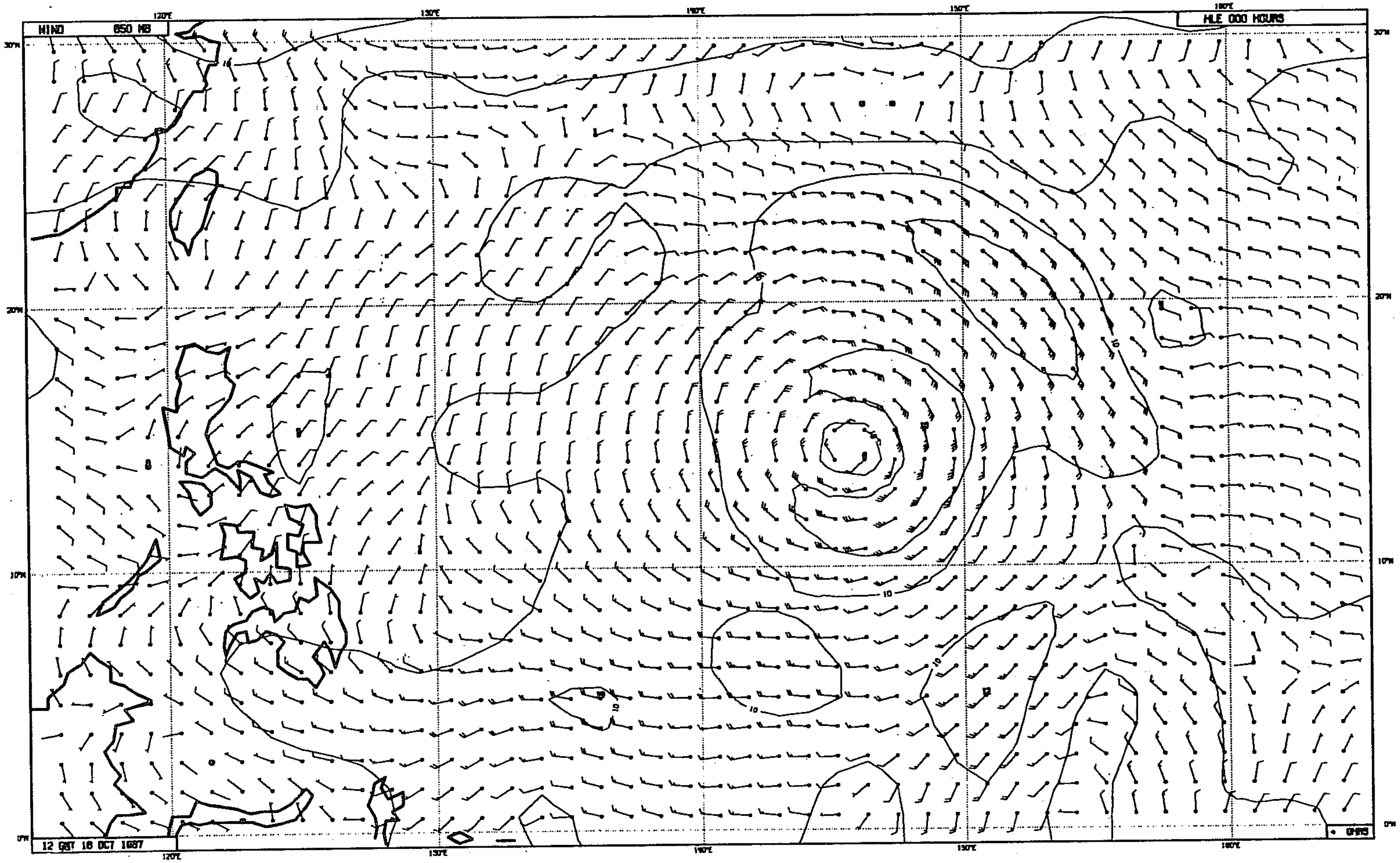

Fig.6b Bogus observations used, otherwise as Fig. 6a.

In addition to the conventional data the Guam forecast centre has available satellite imagery, radar and aircraft observations. Their 'best-track' documentation of LYNN was used as input for generating six-hourly bogus observations by the procedure described above, and data assimilation was run for four days, 16-20 October 1987. Four consecutive 3-day forecasts from the 17th to the 20th at 12 UTC were run and compared with the operational forecasts.

The operational analyses from October 1987 which were used as control do not use the higher resolution structure functions.

6.1 Analyses

At the beginning of the assimilation (on the 16th at 00 UTC), the cyclone was still weak with maximum wind speeds of merely 15 m/s. The intensity increased gradually over the next three and a half days, reaching a maximum of 70 m/s. Providing bogus data every six hours made the development smooth and the analysis increment small throughout the period. It is important to keep the analysis increments as small as possible, as they do not satisfy gradient wind balance.

The operational analysis was able to catch the development reasonably well, probably because of the good coverage of satellite data on the 16th. LYNN was an unusually large system and through the 5-day period the mean positional error in the analyses was 170 km .

The provision of bogus observations puts the position right within 40 km and makes the cyclone better defined. The maximum wind speeds come closer to the centre, about 360 km, and the surface pressure goes down to 987 hPa at its lowest, compared to 600 km and 995 hPa respectively in operations. (See Figs.6a and 6b for the analyses of the 18th). The analysis with the bogus data has slightly higher maximum wind speeds than the operational one later in the assimilation, but it never exceeds 32 m/s, as a result of the limited resolution.

6.2 Forecasts

The ensemble of predicted 3-day storm tracks is plotted in Fig.7 for the experimental and the operational forecasts.

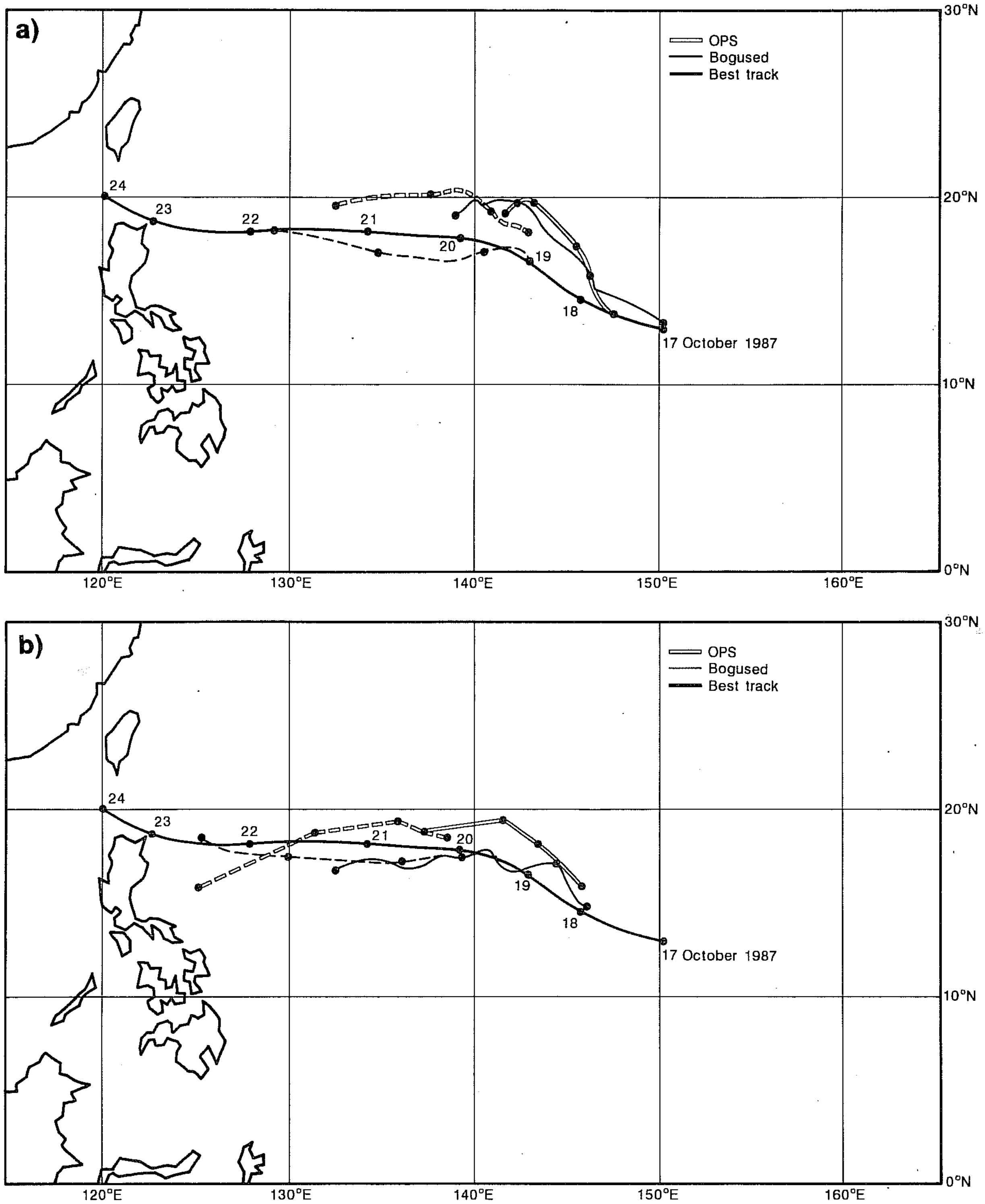

Fig.7. Estimated best track of tropical cyclone LYNN together with 3-day forecasts from bogus and operational analyses, a: forecasts from the 17'th and the 19'th, b: forecasts from the 18'th and the 20'th of October 1987. 24 hours between dots along the trajectories.

The operational forecast moves the system too slowly and the first three forecasts takes it too far to the north. The analyses with the bogus data produce significantly better forecasts in terms of position, speed and direction of motion. Table 2 gives a summary of the positional forecast errors averaged over the four cases.

The forecast development does not reflect the true rapid intensification of the storm. The operational forecast from the 17th deepened the cyclone by 3 hPa in 2 days but the other forecasts, operational or bogus, kept the intensity almost constant in time.

	An	Day1	Day2	Day3
Bogus	30	180	200	210
Operational	170	250	370	410

Table 2. Positional analysis and forecast error in km for bogus and operational runs. Average of four consecutive 3-day forecasts of the LYNN case.

7. CONCLUSIONS AND RECOMMENDATIONS

Given the resolution of the ECMWF data assimilation system, it is not feasible, even with the higher resolution structure functions, to spin up a tropical cyclone of realistic intensity or size. Large bogus wind differences over small distances (smaller than the horizontal length scale of the structure functions) will be misinterpreted and create erroneous analyses. (The model physics is unable to 'fill in' the missing features of the inner region. This suggests that bogus data have to disregard unresolvable features and put the emphasis on the wind structure of the outer region 150 to 600 km). There is evidence that a good description of the outer region is one of the most important factors for successful forecasts of tropical storm motion.

Our experiments have demonstrated that valuable extra information can be assimilated by the analysis system if it is ingested as bogus observations. The technique improves the analysis by correcting the position and by imposing a more realistic wind structure in the outer region. The information survives the initialisation and there is evidence from the LYNN case that it significantly improves the forecast of storm motion.

It is therefore recommended that the necessary implications of a future implementation are investigated further, in particular the acquisition of the additional tropical cyclone data which are required. A cooperation between the regional tropical weather centres and ECMWF on this matter needs to be established.

The format of a standardized telex needs to be drawn up and should at least contain the following parameters: (1) central position, (2) maximum wind speed and (3) radius of maximum wind speed. Windspeed (4) and corresponding radius (5) at some large distance(s) from the centre e.g. radius of gale-force wind are essential, too. Winds should be given for the four quadrants separately if possible, but this is not essential at this stage.

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References

Bengtsson, L., H. Böttger, and M. Kanamitsu, 1982: Simulation of hurricane-type vortices in a general circulation model. Tellus, 34, 440-457.

Dell'Osso, L. and L. Bengtsson, 1985: Prediction of a typhoon using a fine-mesh NWP model. Tellus, 37A, 97-105.

Dvorak, V.F., 1984: Tropical cyclone intensity analysis using satellite data. NOAA Technical Report NESDIS 11, U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Nat.Environ.Sat.Data Inf.Serv., Washington D.C., 44 pp.

Fiorino, M. and R.L. Elsberry, 1986: The role of vortex structure in tropical cyclone motion. Proceedings of the AMS 17'th Conference on Hurricanes and Tropical Meteorology, Miami 7-10 April 1987, 55-59.

Hall, C.D., 1987: Verification of global model forecasts of tropical cyclones during 1986. Meteor.Mag., 116, pp 216-219.

Holland, G.J., 1983: Tropical cyclone motion: environmental interaction plus a beta effect. J.Atmos.Sc., 40, 328-42.

Kanamitsu, M., 1985: Data processing, selection and quality control as used at JMA. Proceedings of the ECMWF workshop on the use and quality control of meteorological observations, Reading 6-9 November 1984, 369-396.

Le Marshall, J.F., W.L. Smith and G.M. Callan, 1985: Hurricane Debby - an illustration of the complimentary nature of VAS soundings and cloud and water vapour motion winds. Bull.Amer.Meteor.Soc., 66, 258-263.

deMaria, M., 1986: The effect of the vortex structure on barotropic hurricane track forecasts. Proceedings of the AMS 17'th Conference on Hurricanes and Tropical Meteorology, Miami 7-10 April 1987, 52-54.

Marks, D.G., 1986: A technique to improve the MFM 12-hour forecast by modifying the spin-up. Proceedings of the AMS 17'th Conference on Hurricanes and Tropical Meteorology, Miami 7-10 April 1987, 64-66.

Mathur, M.B., 1986: NMC's high resolution hurricane model. Proceedings of the AMS 17'th Conference on Hurricanes and Tropical Meteorology, Miami 7-10 April 1987, 60-63.

McBride, J.L., 1981: Observational analysis of tropical cyclone formation. J.Atmos.Sc., 38, 1117-1166.

Milne-Thomson, L.M., 1968: Theoretical Hydrodynamics. MacMillan Press, London, 743 pp.

Quah, L.C. and B.K. Cheang, 1988: Utilization of ECMWF global NWP products on GTS for operational weather forecasting at the Malaysian Meteorological Service (MMS). Proceedings of the WMO technical conference on regional weather prediction with emphasis on the use of global products, ECMWF, Reading, 18-22 April 1988. (Not yet published)

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 tropical easterly wave disturbances over Africa and the Tropical Atlantic. Mon.Wea.Rev., 116, 824-865.

Joint Typhoon Warning Centre, 1987: The 1987 Annual Tropical Cyclone Report.

WMO, 1986: Proceedings of the WMO international workshop on tropical cyclones, Bangkok 25 Nov.- 5 Dec. 1985. WMO/TD No.83.