TECHNICAL MEMORANDUM

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Performance of the ECMWF model in tropical cyclone track forecasting over the Western North Pacific during 1990-1991

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ABSTRACT

The performance of the ECMWF model in tropical cyclone track forecasting was evaluated based on best-track data for storms which occurred over the western North Pacific in 1990 and 1991. The impact of enhanced observations collected by four concurrent field experiments (SPECTRUM, TCM-90, TYPHOON-90 and TATEX) during August and September 1990 was studied. A comparison of the tropical cyclone track forecasting skill for the T106 and T213 models was also performed.

1. INTRODUCTION

Since the ECMWF model was put into operational use more than 12 years ago, there were a number of discussions (Bengtsson et al., 1982; Dell'Osso and Bengtsson, 1985; Heckley et al., 1987; Chan and Lam, 1989) on its capability in simulating tropical cyclones (TCs). Bengtsson et al. (1982) found that the ECMWF operational model was capable to simulate TCs which had a frequency and distribution resembling those observed climatologically. However, limited by the horizontal resolution (1.875° x 1.875°), individual TCs were not well forecast by the model. After the T106 model was implemented, Heckley et al. (1987) and Chan and Lam (1989) performed case studies and the results indicated improvement in the skills of the model in TC track forecasting. However, no comprehensive study has been conducted on the ECMWF model's performance in TC forecasting for relatively large samples since the work of Bengtsson et al. (1982).

The present study evaluated the performance of the ECMWF model in TC track forecasting based on best-track data pertaining to storms which occurred over the western North Pacific in 1990 and 1991.

In August and September 1990, four concurrent field experiments were conducted over the western North Pacific to study TC movement. These experiments were the SPecial Experiment Concerning Typhoon Recurvature and Unusual Motion (SPECTRUM) conducted by the Typhoon Committee of the Economic and Social Commission for Asia and the Pacific (ESCAP)/World Meteorological Organization (WMO) (Lam, 1991), the Tropical Cyclone Motion Experiment (TCM-90) carried out by the US Navy (Harr et al., 1991), the TYPHOON-90 Experiment of the USSR, and the Taiwan Area Typhoon Experiment (TATEX). During Intensive Observation Periods (IOPs), surface and upper-air observations were made at increased frequencies and data were also received from additional sites, including deployed weather ships, buoys, offshore platforms, wind profilers, as well as a deployed DC-8 aircraft. Most of these data were transmitted via the Global Telecommunication System (GTS) and received by the ECMWF to initialize the model. It would therefore be interesting to assess the impact of the enhanced data on the model forecasts and compare the results with those obtained outside the experiments.

In September 1991, the high resolution ECMWF operational analysis and forecasting system at T213 31 levels replaced the old T106 19 level system. The effective horizontal resolution of the T213 model in the free atmosphere is around 100 km at half wavelength. As pointed out by Dell'Osso and Bengtsson (1985), a horizontal resolution equivalent to a grid size of 50 km or less would be required for operational forecasting of TCs. In this connection, it seems that the resolution of the new operational system is still not quite adequate for the purpose. Nevertheless, a comparison of the performance of the T213 and T106 models should be able to reveal the changes, if any, due to the increase in resolution.

2. DATA AND METHODOLOGY

Tables 1 and 2 show the TCs considered in this study.

Best-track data compiled by the Royal Observatory (RO), Hong Kong were used as the "ground-truth" in the verification of ECMWF forecasts if they were available. Since the compilation of best-track data by RO for the 1991 TCs was not completed before the study, data provided by the RSMC Tokyo - Typhoon Center via the GTS were used instead if RO data were not available (the corresponding TCs are marked by asterisks in Table 2).

In order to avoid the difficulties of identifying the centres of ill-defined model vortices which correspond to weak TCs, only those cyclones with maximum sustained winds in excess of 17.2 m/s (i.e., tropical storms, severe tropical storms, and typhoons) were considered. In other words, forecasts were not verified for a tropical depression or after the actual TC had weakened into a tropical depression. Consequently, LEWIS (9002), TD0614, AKA (9013), CECIL, IRA (9022), JEANA and LOLA (9024) of 1990, and DOUG, TD0827 (9113) and HARRY (9114) of 1991 were not included. Nevertheless, there were still a number of cases in which the centres of the model TCs were ill-defined and hence could not be identified, although they only accounted for less than 10 % of the cases considered. No attempts were made to study the phenomenon of TC genesis in the model.

Prognostic charts with isobars of mean sea level pressure, 10 m wind vectors, and locations of local pressure minima plotted by the MAGICS/GKS system (ECMWF, 1988) were manually read to extract the positions of the forecast TCs. An example of the prognostic charts together with the verifying analysis is shown in Figure 1. In general, the positions of the TC centres could be readily determined to the nearest 0.1 degree. In case when there were more than one locations of local pressure minima near the TC centre, the one which agreed best with the vortex centre depicted by the wind field was chosen to be the forecast TC position.

Forecasts at T+24, T+48 and T+72 hours were verified. The forecast error E_M for each case was expressed in terms of the great circle distance between the forecast position and the verifying best-track location. Forecasts based on the persistence (PER) method were also computed by linear extrapolation of the 12 hour movement implied by the best-track positions at the initial time T and at T-12 hours, and the corresponding errors E_P were obtained for comparison. Using a similar approach as DeMaria (1987), the relative error compared to the PER method (R) was calculated for each case using :

$$R\ (\%) = 100 \cdot \frac{E_P - E_M}{E_P + E_M}$$

If the model performs better than the PER method (i.e., $E_M < E_P$), then R has a positive value. Otherwise, if the model forecast is worse than that of the PER method (i.e., $E_M > E_P$), then R has a negative value. In other words, R is a measure of the skill of the model relative to the PER method.

Apart from E_M and R, the two components of the ECMWF forecast errors were also computed so as to identify any systematic error. Using a rotated co-ordinate system with the Y-axis parallel to the observed storm motion over the corresponding forecast interval, the cross-track (CT) and along track (AT) error components were obtained and plotted. Any systematic northward bias as observed by Ueno (1991) can then be identified by a shift of the plots towards the lower right-hand quadrant.

Following Ueno (1989), the sample was also categorized according to the three different stages of TC movement: BEFORE, DURING and AFTER recurvature. These stages were determined by the 48-hour actual TC movement according to the criteria in Table 3.

To examine the impact of enhanced observational data during the field experiments, the sample of 1990 was divided into two: one consisting of the seven SPECTRUM TCs, namely WINONA, YANCY, ABE, DOT, ED, FLO and GENE ("SPECTRUM 1990") and the other one containing the rest ("Non-SPECTRUM 1990"). Similarly, comparison of the performance of the T213 and T106 models was carried out by splitting the sample of 1991 into two: one consisting of the cases which occurred before 17 September 1991 ("T106 1991") and the other one containing the rest ("T213 1991"). Please note that both LUKE and MIREILLE were present during the transition and the corresponding cases were separated accordingly. In order to obtain a larger T106 sample for the study, the "Non-SPECTRUM 1990" sample was also combined with the "T106 1991" sample to give a larger "T106 (Non-SPECTRUM) 90-91" sample.

3. VERIFICATION RESULTS

Tables 4 to 8 show the verification statistics for the mean forecast errors $\langle E_M \rangle$ and $\langle E_P \rangle$, standard deviations of the forecast errors, mean relative errors $\langle R \rangle$ and the number of cases for the different stages of TC movement and the various samples. In general, the numbers of BEFORE recurvature cases dominate and therefore the results of the combined samples (ALL) are expected to have similar characteristics as the BEFORE samples. Please note that the numbers of cases for the DURING and AFTER stages are sometimes small and this should be borne in mind when interpreting the corresponding results. Also, the mean relative errors $\langle R \rangle$ were obtained by averaging the individual R values over the sample concerned and so they are not necessary the same as those computed by using $\langle E_M \rangle$ and

<E_P> (not shown).

As a whole, without considering the different stages of TC movement, the mean forecast error for the "SPECTRUM 1990" sample is the smallest for T+24 hour forecasts (151 km) whereas the mean errors for the "T213 1991" sample are the smallest for T+48 and T+72 hour forecasts (248 km and 355 km respectively). This observation is also reflected in Figure 2 (a) which shows the plots of <R> for ALL cases. It is apparent that both the enhanced observational data during the field experiments and the increase in model resolution brought about similar improvement (around 5 to 10 %) in the skill of the ECMWF model in TC track forecasting. The model also performed better than the PER method starting at T+24 hours for these two samples. Although <R> is rather small at T+24 hours, it rises to around 20 % and 25 % at T+48 and T+72 hours respectively. It should also be noted that apart from the small forecast errors, the corresponding standard deviations for these two samples are also less than the others.

Turning to the BEFORE recurvature cases, the model still performed best (in terms of forecast errors) at T+24 hours for the "SPECTRUM 1990" sample and at T+72 hours for the "T213 1991" sample, with errors of 151 km and 301 km respectively. However, Figure 2 (b) shows that the model could not "beat" the PER method at T+24 hours even with enhanced observational data or higher resolution. In fact, at T+24 hours, the model performed significantly better only during the experiment period. The T213 model does not have any superiority over the T106 model in this respect. Nonetheless, the opposite is true at T+72 hours - there is a more than 10 % improvement of the T213 forecasts compared with the other samples. This improvement is also found at T+48 hours although the magnitude is somewhat less. Judging from these results, it becomes apparent that the increase in observational data density (both temporal and spatial) contributed to improvement of the ECMWF forecasts only at T+24 hours. It can therefore be postulated that the positive impact of the enhanced data was gradually off-set by the inadequacy of the T106 model to simulate the structure and development of TCs. On the other hand, the increase in resolution of the T213 model brought about improvement after 24 hours irrespective of the relatively low skill at T+24 hours. Before going on to the DURING and AFTER recurvature cases, it is worth mentioning that the "T106 1991" sample also shows an improvement similar to that of the "T213 1991" sample at T+48 hours although not at T+72 hours. This point will be discussed in the following sections.

Considering Figures 2 (c) and (d) for the DURING and AFTER recurvature cases respectively, it can be observed that the model performed better than the PER method except for the T106 "Non-SPECTRUM" forecasts at T+24 hours for DURING recurvature cases. However, <R> starts to decline after 48 hours for most cases. This decrease, especially that observed in the "T213 1991" sample for the AFTER recurvature cases, is contrary to the monotonic increasing trends for most the BEFORE recurvature cases. Unfortunately, the numbers of cases are small for the T+72 hours and therefore a definite conclusion cannot be made. Also, the improvement in the skill for the "SPECTRUM 1990" sample may not be as dramatic as indicated.

Despite the small sizes of the DURING and AFTER samples, they can nevertheless be combined into larger DURING/AFTER samples. The mean relative errors <R> and the corresponding number of cases are summarized in Table 9. Apart from the "SPECTRUM 1990" sample in which the numbers of cases are still small, the larger sample sizes of the others should give more weights to the trends and differences indicated. Figure 3 shows the <R> plots for the combined samples. The general trend of increase in skill (relative to the PER method) from T+24 to T+48 hours and the subsequent decrease at T+72 hours is evident. The T+24 and T+48 hour skills are also larger than those for the BEFORE stage. This is thought to be due to the model's capability in forecasting recurvature correctly whereas the PER method should not be able to do so. However, the decline in skill at T+72 hours, which was also observed by Chan et al. (1987) in assessing the performance of the US Navy Nested Tropical Cyclone Model (NTCM) for high latitude storms, cannot be easily understood. It should also be noted that the decrease pertaining to the "T213 1991" sample is the most significant and the T213 model appears to have no additional skill over the T106 model in this respect.

4. SYSTEMATIC BIAS

Figures 4 to 8 show the plots of the CT and AT error components for the different samples. It is apparent that the T106 forecasts have a systematic bias towards the lower right-hand quadrant (relative to the best-track) starting at T+24 hours and this becomes more significant towards T+72 hours. The plots which correspond to the BEFORE recurvature stage can almost account for this bias completely. This strongly indicates that the T106 model has a right-hand bias for the BEFORE cases, i.e., it tends to forecast early recurvature of TCs and hence leading to northward (and possibly also slow) bias. This is also true for the "SPECTRUM 1990" sample even though the observational data were enhanced. The lack of improvement of the T+48 and T+72 hour "SPECTRUM forecasts" over the "Non-SPECTRUM forecasts" can be attributed to this systematic bias.

In contrary, the "T213 1991" sample does not show such a large right-hand bias. In order to visualize the difference more clearly, plots of the mean CT and AT error components are shown in Figure 9. Considering ALL cases (Figure 9 (a)), it is obvious that the T213 model forecasts have the least systematic bias although the tendency to forecast early recurvature has not been removed completely. It is also surprising that the "SPECTRUM forecasts" give the most significant right-hand bias.

Considering the BEFORE recurvature cases (Figure 9 (b)), the right-hand bias is more prominent. The T213 forecasts remain the least biased whereas the "SPECTRUM forecasts" are still the worst in this regard. In addition, a definite trend in the decrease in bias can be seen: from "SPECTRUM 1990" to "Non-SPECTRUM 1990", "T106 1991" and finally "T213 1991". The reduction in the bias for the "T106 1991" sample compared to the "Non-SPECTRUM 1990" sample, especially at T+48 hours, is consistent with the good skill indicated by <R> in Figure 2 (b).

There is not any significant systematic bias nor difference between the different samples for the DURING recurvature cases (Figure 9 (c)).

Although the numbers of cases for the AFTER recurvature cases are relatively small, Figure 9 (d) suggests systematic biases of different nature. On the one hand, the T106 forecasts all have left-hand bias and the most significant one pertains to the "T106 1991" sample. On the other hand, the T213 forecasts seem to behave differently with a fast right-hand bias at T+72 hours. This may account for the decrease in skill at T+72 hours observed in Figure 2 (d) and Figure 3.

Lastly, it is interesting to note that despite the relatively large systematic errors observed for the forecasts, there is no such bias in the analyzed TC positions (marked by squares in Figure 9).

5. DISCUSSIONS

In view of the verification results shown in the previous sections, a few points can be summarized here for discussion. Firstly, the enhanced observational data collected during the field experiments in 1990 led to improvement of the ECMWF model in TC track forecasting, especially at T+24 hours for the BEFORE recurvature TCs and also possibly at T+48 and T+72 hours for the DURING/AFTER recurvature TCs. However, the T106 model, limited by its resolution to resolve the detailed structure of TCs, failed to perform better at T+48 and T+72 hours for the BEFORE recurvature TCs despite the enhanced data. Furthermore, if the improvement shown at T+48 and T+72 hours for the DURING/AFTER recurvature cases is genuine (which unfortunately is not certain due to the small sample sizes), it will then be contrary to the results for the BEFORE recurvature cases. Does this mean that the increase in spatial and temporal resolution of observations had a larger positive impact on the model's performance at T+48 and T+72 hours in the baroclinic region whereas the increase was still inadequate for the barotropic region? Or perhaps, given the enhanced data, the resolution of the T106 model was sufficiently high for making better forecasts at T+48 and T+72 hours in the higher latitudes whereas it was still inadequate for the tropics. This latter point seems to be supported by the behaviour of the T213 model.

Secondly, the higher resolution T213 model is found to perform better than the T106 model in TC track forecasting. This improvement is three-fold:

(a) reduction in forecast errors and increase in skill relative to the PER forecasts, especially at T+48 and T+72 hours for the BEFORE recurvature TCs,

(b) reduction in the right-hand systematic bias relative to the best-track (or the northward bias in an earth-oriented coordinate system), and

(c) reduction in the standard deviation of the forecast errors.

The reduction of the northward bias by a higher resolution model was also demonstrated by Ueno (1991) based on the Typhoon Model (TYM) of the Japan Meteorological Agency.

Thirdly, while the enhanced observational data collected during the field experiments led to improvement in the T+24 hour forecasts for BEFORE recurvature cases, the T213 model T+24 hour forecasts do not show any improvement over the T106 model forecasts. This seems to support the last concluding remarks of Dell'Osso and Bengtsson (1985), at least for BEFORE recurvature cases, that "an accurate initial state is a prerequisite for an accurate prediction, and, in some respects this may be more important the shorter the range of the forecast."

Fourthly, the drop in skill of the T213 model at T+72 hours for the DURING/AFTER recurvature cases is a surprising and disturbing result although the relatively small sample size should be borne in mind. Nevertheless, this observation justifies a more in-depth study when more results become available later in 1992.

Fifthly, it is difficult to explain the improvement in skill for BEFORE recurvature cases at T+48 hours and the corresponding decrease of the right-hand bias for the "T106 1991" sample compared to the T106 forecasts in 1990. A change in the usage of satellite soundings data which took place in May 1991 may be the candidate to account for the difference but further studies have to be carried out to determine the physical reason behind it.

Lastly, in order to understand the inadequacy of the T213 model, it is interesting to look at cases with large forecast errors. For T+24, T+48 and T+72 hours respectively, the cases with the three largest errors were selected and the details are given in Table 10. Although there are a total of nine cases, only four TCs are involved: MIREILLE, PAT, ORCHID and YURI. These cases can be classified into three categories:

(a) Typical right-hand bias situations for BEFORE recurvature cases - MIREILLE and ORCHID,
(b) AFTER recurvature case - YURI, and
(c) Binary TC situations - MIREILLE and PAT.

Considering the case of ORCHID, Figure 10 shows that the T213 model had the tendency to forecast early recurvature of the typhoon on 8 October. This example indicates that the T213 model can still have very large right-hand bias for BEFORE recurvature TCs although on the average it should be better than the T106.

YURI accelerated rapidly after its recurvature during 29-30 November. Although the T213 model managed to forecast the recurvature, the rapid acceleration towards the northeast was poorly forecast at T+72 hours based on the 28 November 12 UTC analysis (Figure 11).

The cases of MIREILLE and PAT deserve special attention. During the period 19-21 September, the T213 model had difficulty to represent realistically the vortex of MIREILLE (see Figure 12 for example) despite the fact that it had already intensified into a typhoon shortly before 17 September. Furthermore, the model failed to develop the weak vortex associated with MIREILLE and hence the forecasts remained poor over the period. At the same time, MIREILLE was approaching NAT to the southeast of Taiwan and by 21 September, their separation was less than 1400 km. Binary interactions between the TCs could have taken place and the failure of the model to simulate these interactions correctly might also contribute to the poor forecasts.

Similarly, PAT and ORCHID were also binary cyclones. Their separation decreased from about 1500 km on 10 October to around 1300 km on 12 October (Figure 13). They also rotated anti-clockwisely relative to each other during the period. It is likely that the model again failed to forecast the interactions between the two storms correctly and hence produced poor forecasts for PAT.

The examples of binary cyclones MIREILLE/NAT and PAT/ORCHID suggest that the high resolution T213 analysis and forecasting system has difficulty in obtaining realistic vortex representation and simulating binary interactions correctly. In fact, this problem was also addressed by Chan and Lam (1989) in a case study based on the ECMWF T106 model. It therefore appears that the increase in resolution may not be adequate for forecasting binary TCs and the lack of observational data over the tropical oceans is still a major problem for accurate TC track forecasting. As demonstrated by Andersson and Hollingsworth (1988) and Ueno (1989), the available bogussing techniques can lead to improvement of NWP models in TC track forecasting and the operational use of these methods at the ECMWF should therefore be considered.

6. SUMMARY AND CONCLUSIONS

An evaluation of the performance of the ECMWF model in TC track forecasting for storms which occurred over the western North Pacific in 1990 and 1991 was carried out. It was found that the increase in temporal and spatial density of observational data collected during four concurrent field experiments in August and September 1990 had positive impact on the model's skill in TC track forecasting. However, the enhanced data had no significant impact on the T+48 and T+72 hour forecast skills for BEFORE recurvature cases and this may be due to the relatively low resolution of the T106 model which brought about large systematic right-hand bias in the forecasts.

The higher resolution T213 model appeared to perform better than the T106 model. In particular, the systematic right-hand bias (or northward bias) of the T106 model for BEFORE recurvature TCs was significantly reduced. However, in some occasions, the T213 model still failed to obtain good vortex representation of the TCs and simulate TC interactions realistically.

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Number	Name	Period of Study	No. of Dates
9001	KORYN	13 - 15 JAN	3
9003	MARIAN	16 - 17 MAY	2
9004	NATHAN	16 JUN	1
9005	OFELIA	18 - 23 JUN	6
9006	PERCY	21 - 28 JUN	8
9007	ROBYN	9 JUL	1
9008	STEVE	26 - 30 JUL	5
9009	TASHA	28 - 29 JUL	2
9010	VERNON	30 JUL - 7 AUG	9
9011	WINONA*	7 - 9 AUG	3
9012	YANCY*	14 - 20 AUG	7
9014	ZOLA	18 - 21 AUG	4
9015	ABE*	26 - 31 AUG	6
9016	BECKY	25 - 28 AUG	4
9017	DOT*	4 - 7 SEP	4
9018	ED*	12 - 18 SEP	7
9019	FLO*	13 - 18 SEP	6
9020	GENE*	24 - 28 SEP	5
9021	HATTIE	2 - 6 OCT	5
9023	KYLE	16 - 20 OCT	5
9025	MIKE	8 - 16 NOV	9
9026	NELL	10 NOV	1
9027	OWEN	20 - 28 NOV	9
9028	PAGE	23 - 29 NOV	7
9029	RUSS	14 - 22 DEC	9

Table 1 - List of Tropical Cyclones Selected for the Study (1990)
(* SPECTRUM Tropical Cyclones)

Number	Name	Period of Study	Number of Dates
9101	SHARON*	7 - 11 MAR	5
9102	TIM*	22 - 25 MAR	4
9103	VANESSA*	26 APR	1
9104	WALT	7 - 15 MAY	9
9105	YUNYA	12 - 13 JUN	2
9106	ZEKE	11 - 12 JUL	2
9107	AMY	16 - 18 JUL	3
9108	BRENDAN	21 - 22 JUL	2
9109	CAITLIN*	24 - 28 JUL	5
9110	ELLIE*	11 - 16 AUG	6
9111	FRED	13 - 16 AUG	4
9112	GLADYS*	16 - 22 AUG	7
9115	IVY*	3 - 9 SEP	7
9116	JOEL	5 SEP	1
9117	KINNA*	11 - 12 SEP	2
9118	LUKE*	15 - 18 SEP	4
9119	MIREILLE*	16 - 26 SEP	11
9120	NAT	18 - 22 SEP & 29 - 30 SEP	7
9121	ORCHID*	4 - 12 OCT	9
9122	PAT*	6 - 11 OCT	6
9123	RUTH	20 - 27 OCT	8
9124	SETH*	1 - 12 NOV	12
9125	THELMA*	4 - 5 NOV	2
9126	VERNE*	7 - 10 NOV	4
9127	WILDA*	15 - 18 NOV	4
9128	YURI*	23 - 30 NOV	8
9129	ZELDA*	29 NOV - 2 DEC	4

Table 2 - List of Tropical Cyclones Selected for the Study (1991)
(* Best-track Data Provided by the RSMC Tokyo)

Stage	Direction of Movement (Degrees)
BEFORE	180 - 319
DURING	320 - 9
AFTER	10 - 179

Table 3 - Criteria for the Definition of the Three Stages of TC Movement

Stage of Movement	Forecast Period (hr)	Method	Mean Error (km)	Standard Deviation (km)	Mean R (%)	No. of Cases
BEFORE	T+24	ECMWF	151	72	-3	25
		PER	173	129		
	T+48	ECMWF	302	126	7	22
		PER	407	257		
	T+72	ECMWF	480	202	17	19
		PER	748	383		
DURING	T+24	ECMWF	112	49	16	4
		PER	143	23		
	T+48	ECMWF	196	125	48	4
		PER	509	155		
	T+72	ECMWF	377	81	41	3
		PER	955	402		
AFTER	T+24	ECMWF	168	89	15	9
		PER	247	123		
	T+48	ECMWF	165	98	53	5
		PER	641	348		
	T+72	ECMWF	298	64	55	2
		PER	1291	873		
ALL	T+24	ECMWF	151	74	3	38
		PER	187	124		
	T+48	ECMWF	266	132	20	31
		PER	458	270		
	T+72	ECMWF	452	190	23	24
		PER	819	434		

Table 4 - Verification of ECMWF Forecasts of TC Positions (SPECTRUM 1990)

Stage of Movement	Forecast Period (hr)	Method	Mean Error (km)	Standard Deviation (km)	Mean R (%)	No. of Cases
BEFORE	T+24	ECMWF	174	98	-11	43
		PER	139	79		
	T+48	ECMWF	236	139	14	38
		PER	337	216		
	T+72	ECMWF	301	171	27	32
		PER	564	361		
DURING	T+24	ECMWF	135	67	5	8
		PER	154	63		
	T+48	ECMWF	196	70	22	6
		PER	388	259		
	T+72	ECMWF	354	130	19	5
		PER	916	749		
AFTER	T+24	ECMWF	179	96	24	20
		PER	347	223		
	T+48	ECMWF	305	124	35	14
		PER	806	562		
	T+72	ECMWF	571	173	21	8
		PER	998	658		
ALL	T+24	ECMWF	171	94	1	71
		PER	200	162		
	T+48	ECMWF	248	133	20	58
		PER	455	385		
	T+72	ECMWF	355	194	25	45
		PER	680	496		

Table 5 - Verification of ECMWF Forecasts of TC Positions (T213 1991)

Stage of Movement	Forecast Period (hr)	Method	Mean Error (km)	Standard Deviation (km)	Mean R (%)	No. of Cases
BEFORE	T+24	ECMWF	203	124	-12	75
		PER	146	96		
	T+48	ECMWF	289	203	8	63
		PER	344	226		
	T+72	ECMWF	444	319	15	55
		PER	627	402		
DURING	T+24	ECMWF	185	137	-1	34
		PER	177	110		
	T+48	ECMWF	290	198	16	27
		PER	470	334		
	T+72	ECMWF	411	258	16	20
		PER	735	613		
AFTER	T+24	ECMWF	226	180	13	29
		PER	267	155		
	T+48	ECMWF	367	276	34	17
		PER	699	415		
	T+72	ECMWF	419	278	31	7
		PER	1117	916		
ALL	T+24	ECMWF	203	140	-4	138
		PER	179	123		
	T+48	ECMWF	301	215	14	107
		PER	432	315		
	T+72	ECMWF	433	299	16	82
		PER	695	526		

Table 6 - Verification of ECMWF Forecasts of TC Positions (T106 90-91)

Stage of Movement	Forecast Period (hr)	Method	Mean Error (km)	Standard Deviation (km)	Mean R (%)	No. of Cases
BEFORE	T+24	ECMWF	235	132	-14	42
		PER	166	111		
	T+48	ECMWF	353	232	4	38
		PER	394	263		
	T+72	ECMWF	504	362	15	36
		PER	712	448		
DURING	T+24	ECMWF	189	156	1	22
		PER	189	125		
	T+48	ECMWF	277	208	19	17
		PER	506	379		
	T+72	ECMWF	345	193	20	12
		PER	763	635		
AFTER	T+24	ECMWF	202	178	17	18
		PER	242	149		
	T+48	ECMWF	292	281	37	11
		PER	572	339		
	T+72	ECMWF	372	268	25	5
		PER	806	654		
ALL	T+24	ECMWF	216	149	-3	82
		PER	189	126		
	T+48	ECMWF	323	234	14	66
		PER	453	312		
	T+72	ECMWF	455	327	17	53
		PER	732	504		

Table 7 - Verification of ECMWF Forecasts of TC Positions (Non-SPECTRUM 1990)

Stage of Movement	Forecast Period (hr)	Method	Mean Error (km)	Standard Deviation (km)	Mean R (%)	No. of Cases
BEFORE	T+24	ECMWF	161	99	-10	33
		PER	120	67		
	T+48	ECMWF	191	85	14	25
		PER	268	123		
	T+72	ECMWF	330	174	14	19
		PER	467	234		
DURING	T+24	ECMWF	176	99	-4	12
		PER	155	75		
	T+48	ECMWF	311	190	12	10
		PER	407	243		
	T+72	ECMWF	510	321	8	8
		PER	694	617		
AFTER	T+24	ECMWF	266	185	6	11
		PER	307	162		
	T+48	ECMWF	504	226	27	6
		PER	930	469		
	T+72	ECMWF	537	371	46	2
		PER	1895	1277		
ALL	T+24	ECMWF	185	125	-5	56
		PER	164	117		
	T+48	ECMWF	266	177	15	41
		PER	399	321		
	T+72	ECMWF	394	242	14	29
		PER	628	568		

Table 8 - Verification of ECMWF Forecasts of TC Positions (T106 1991)

Forecast Period (hr)	SPECTRUM (1990)	T213 (1991)	T106 (Non-SPECTRUM 90-91)	T106 (Non-SPECTRUM 1990)	T106 (1991)
T+24	15 (13)	19 (28)	5 (63)	8 (40)	1 (23)
T+48	51 (9)	31 (20)	23 (44)	26 (28)	18 (16)
T+72	47 (5)	20 (13)	20 (27)	21 (17)	16 (10)

Table 9 - Skill as Given by the Average Relative Errors for the DURING/AFTER Recurvature Cases (Number of cases given in brackets)

Forecast Period (hr)	Name of Tropical Cyclone	Date of Analysis	Verifying Best-track Position	Forecast Position	Forecast Error (km)	Stage of Movement
T+24	MIREILLE	19 SEP	15.0 N 140.6 E	17.3 N 143.9 E	435	BEFORE
	PAT	10 OCT	27.6 N 151.3 E	31.3 N 149.9 E	433	AFTER
	MIREILLE	20 SEP	14.8 N 136.1 E	17.0 N 139.3 E	421	BEFORE
T+48	MIREILLE	19 SEP	14.8 N 136.1 E	19.2 N 139.1 E	584	BEFORE
	MIREILLE	21 SEP	18.8 N 130.7 E	21.5 N 135.3 E	566	BEFORE
	PAT	9 OCT	27.6 N 151.3 E	32.5 N 150.4 E	552	AFTER
T+72	PAT	9 OCT	35.9 N 152.9 E	42.7 N 157.4 E	849	AFTER
	ORCHID	5 OCT	22.1 N 130.5 E	27.7 N 136.2 E	847	BEFORE
	YURI	28 NOV	32.3 N 154.2 E	26.0 N 150.1 E	806	AFTER

Table 10 - Cases with the Three Largest Forecast Errors for the T213 Model

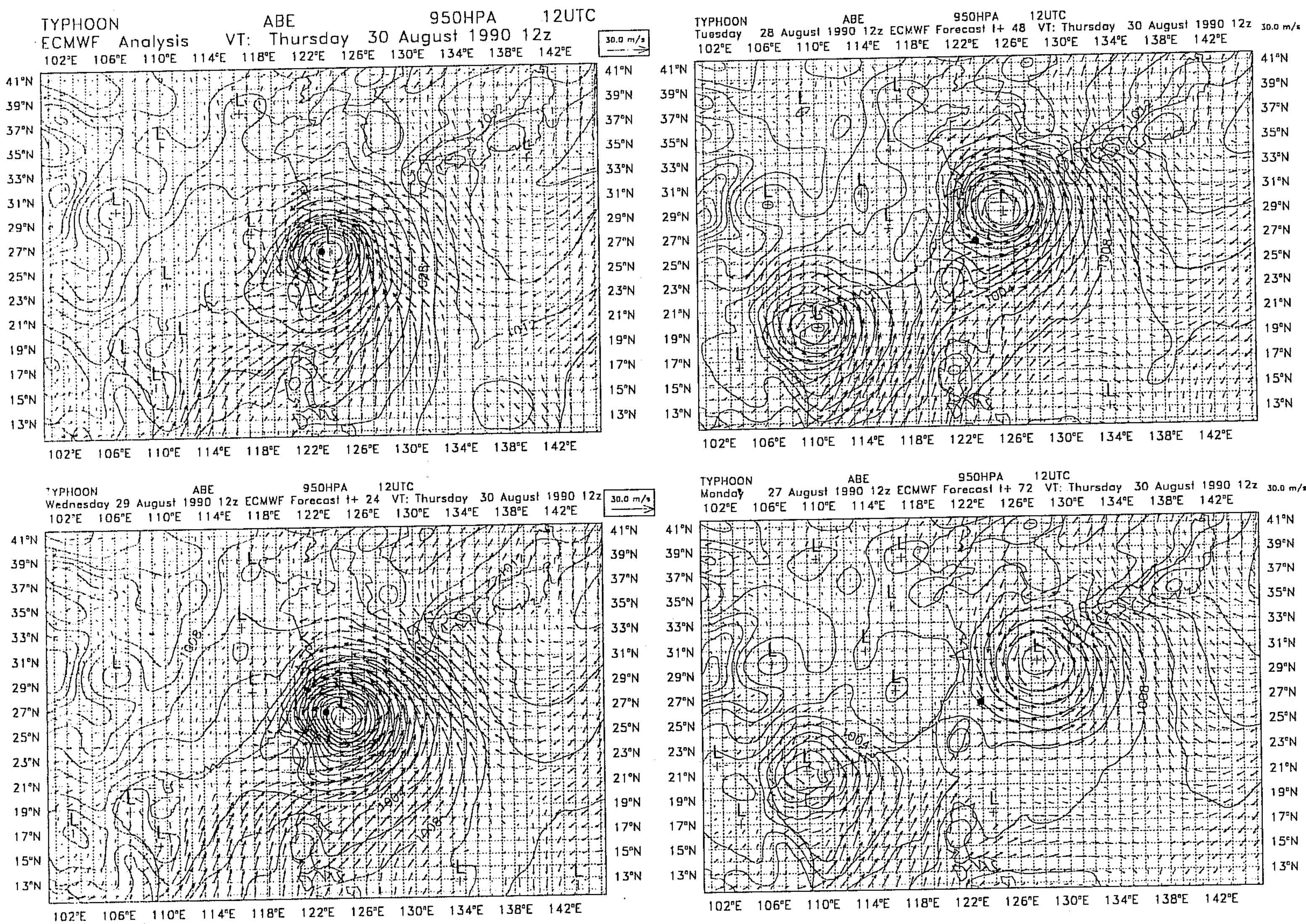


Figure 1 - Example of a Set of T+24, T+48 and T+72 hour ECMWF TC Prognostic Charts Together with the Verifying Analysis (The black dot at the centre of each chart indicates the verifying best-track position)

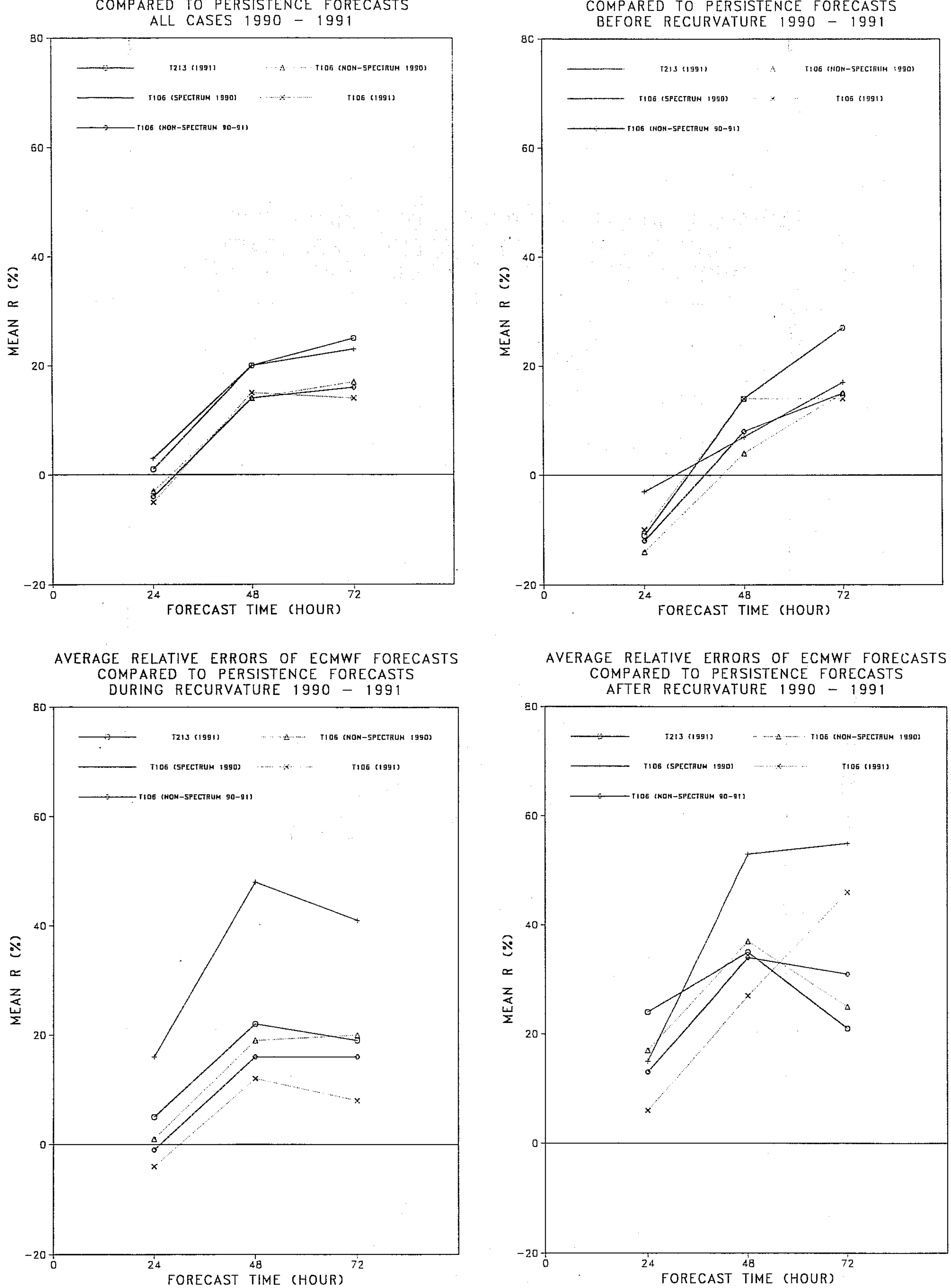


Figure 2 - Skill as Given by the Average Relative Errors of ECMWF Forecasts Compared to Persistence Forecasts 1990-1991

(a) ALL Cases
(b) BEFORE Recurvature
(c) DURING Recurvature
(d) AFTER Recurvature

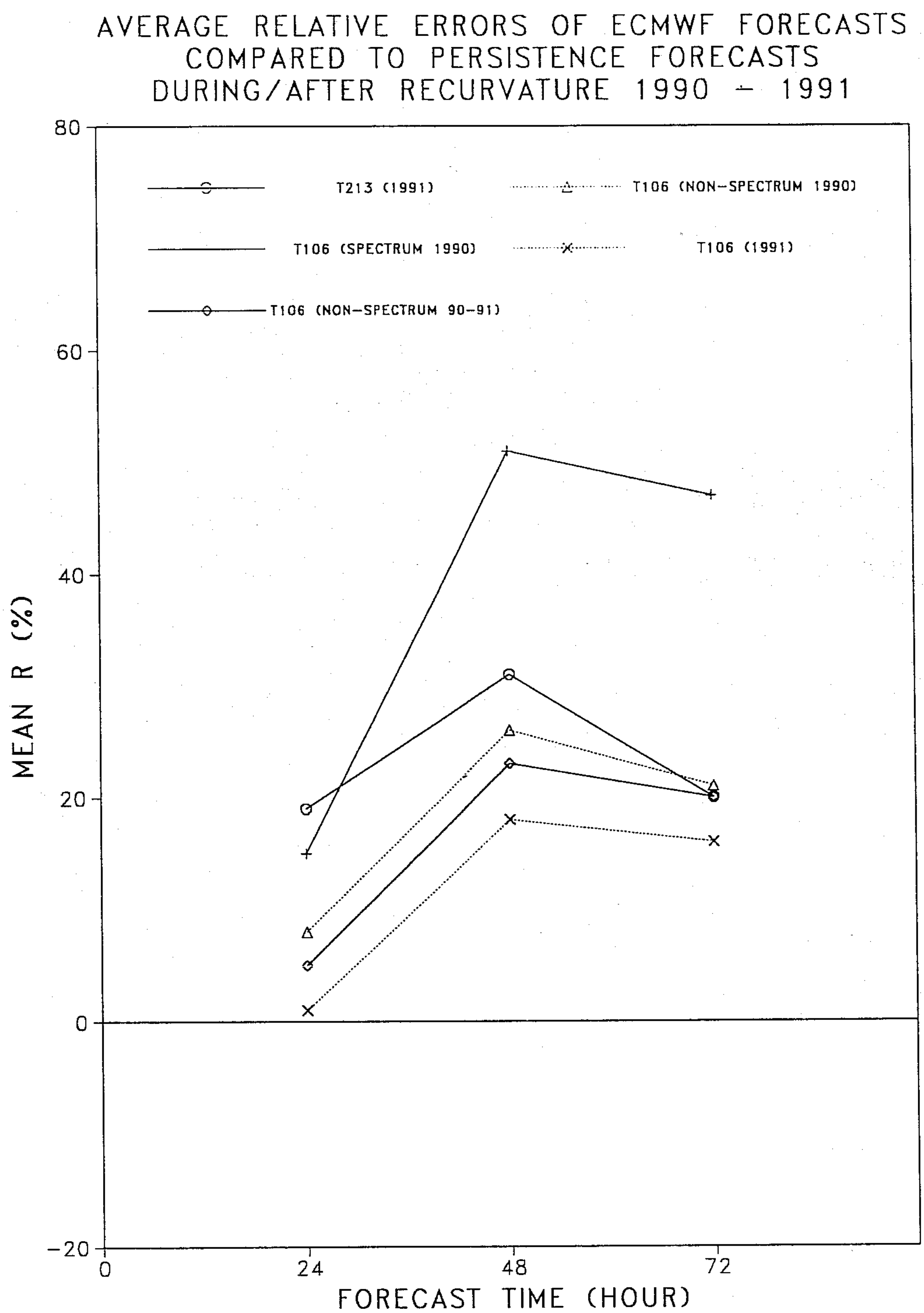


Figure 3 - Skill as Given by the Average Relative Errors of ECMWF Forecasts Compared to Persistence Forecasts for DURING/AFTER Recurvature Cases 1990-1991

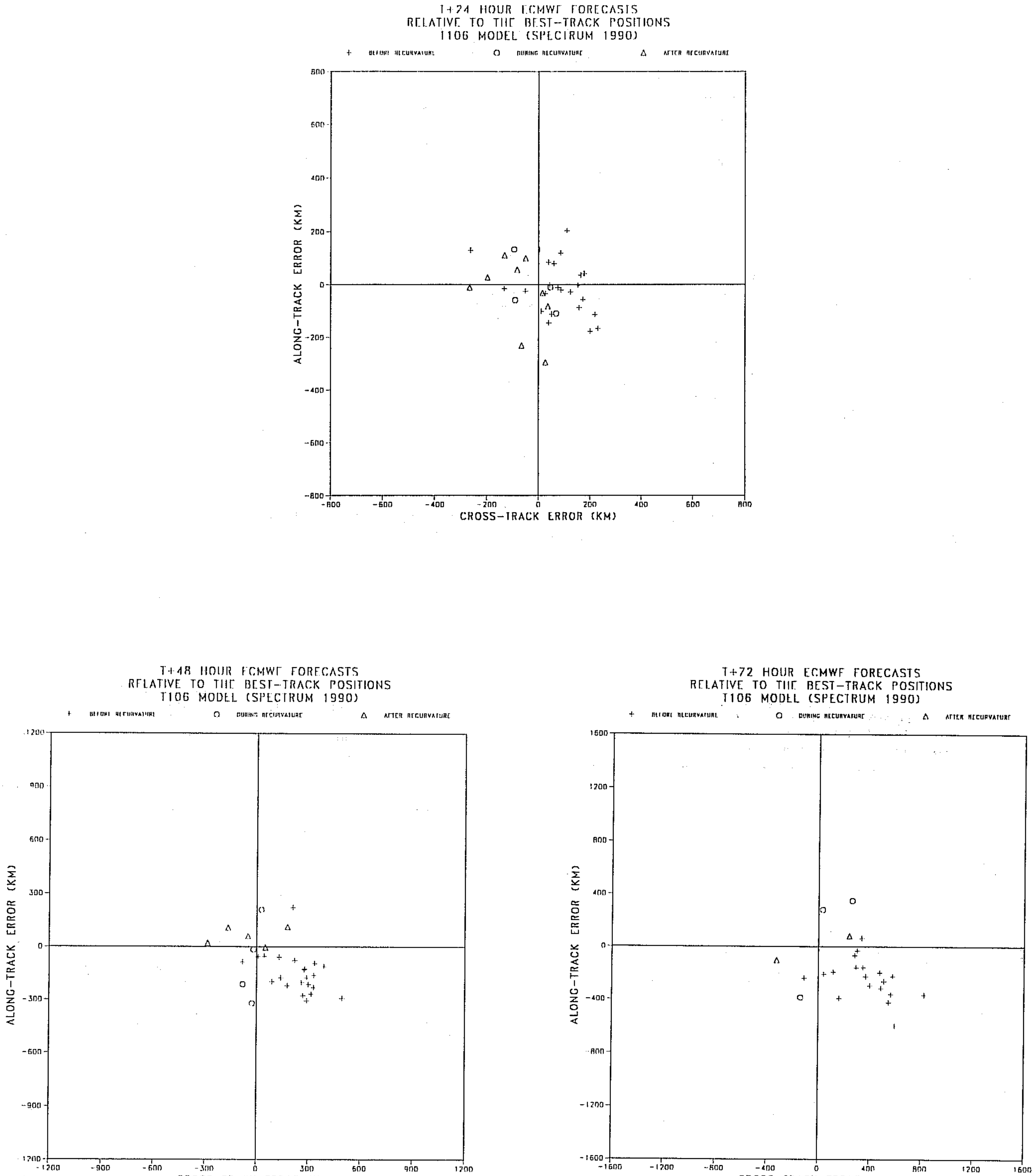


Figure 4 - ECMWF Forecasts Relative to the Best-track Positions for "SPECTRUM 1990"

(a) T+24 hours (b) T+48 hours (c) T+72 hours

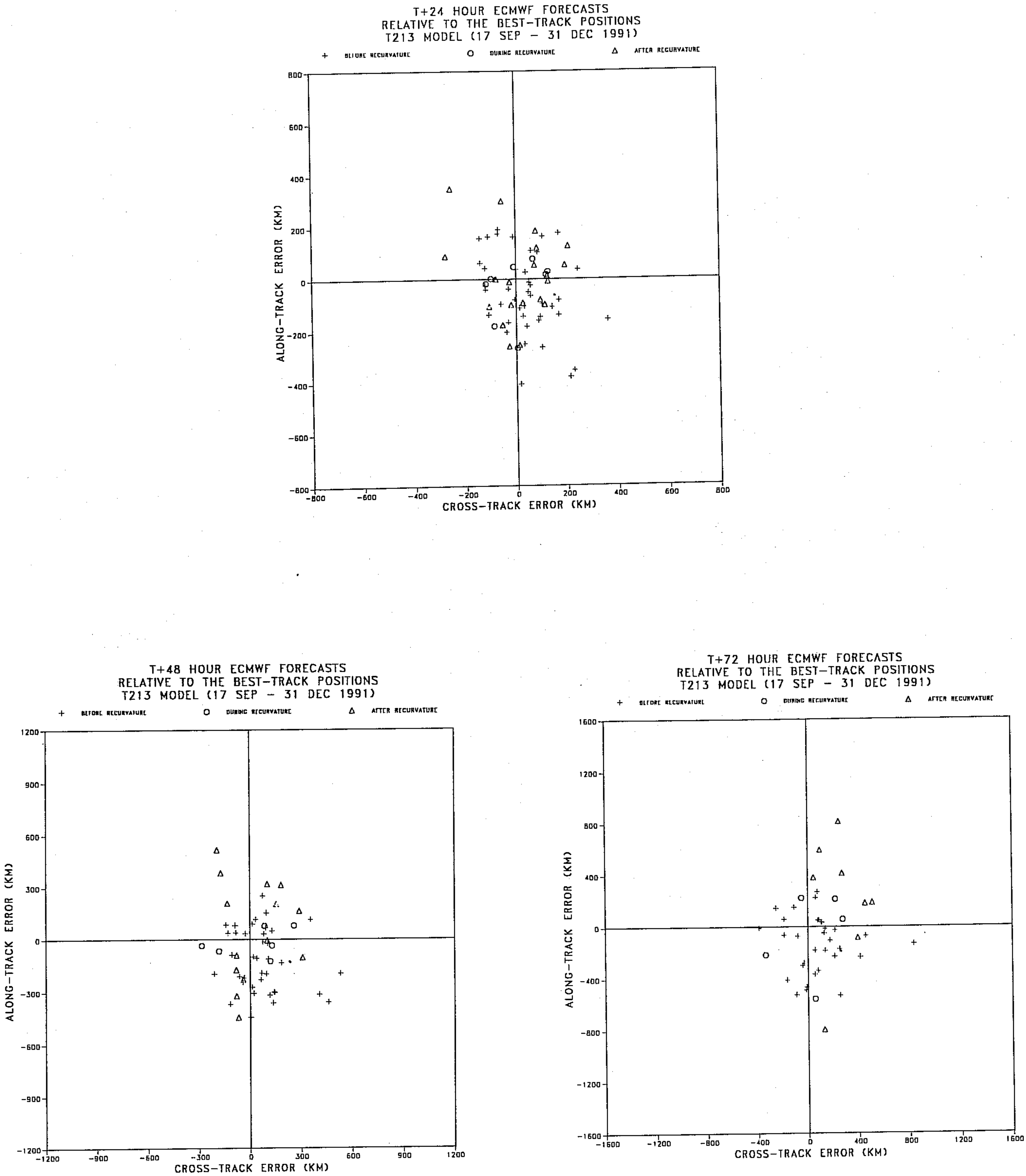
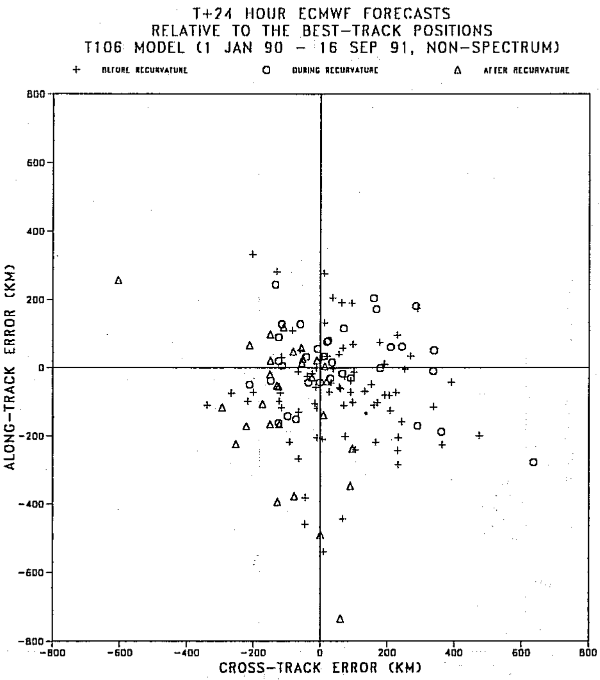
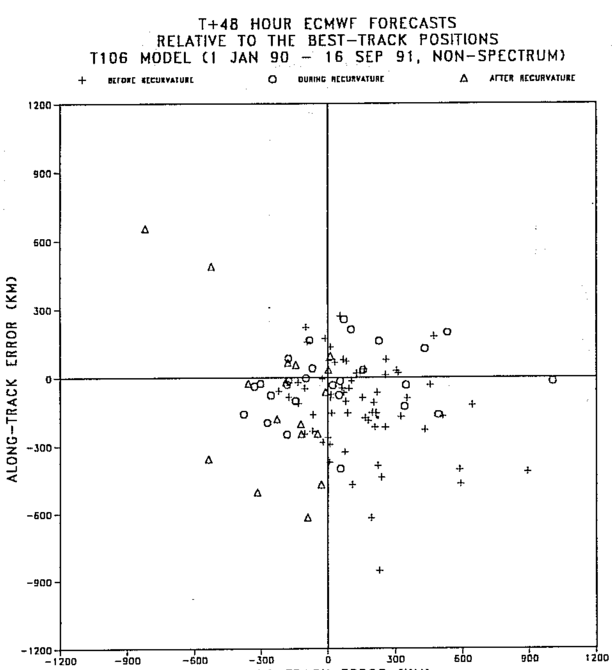


Figure 5 - ECMWF Forecasts Relative to the Best-track Positions for "T213 1991"

(a) T+24 hours (b) T+48 hours (c) T+72 hours





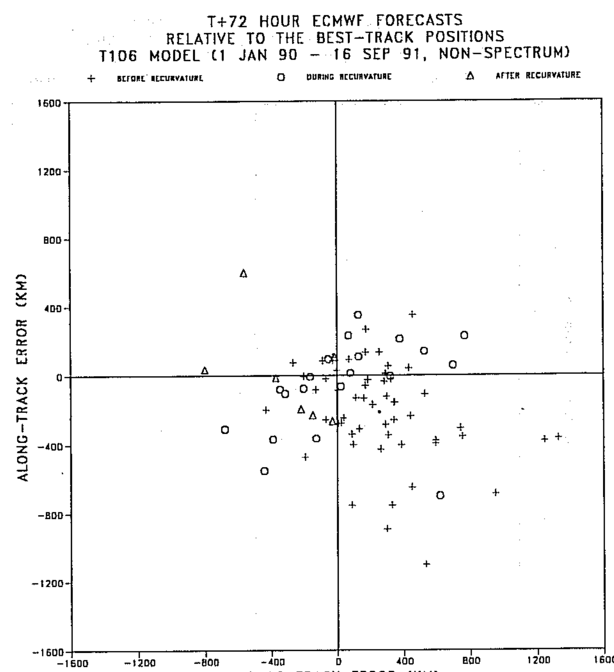


Figure 6 - ECMWF Forecasts Relative to the Best-track Positions for "T106 (Non-SPECTRUM 90-91)"

(a) T+24 hours (b) T+48 hours (c) T+72 hours

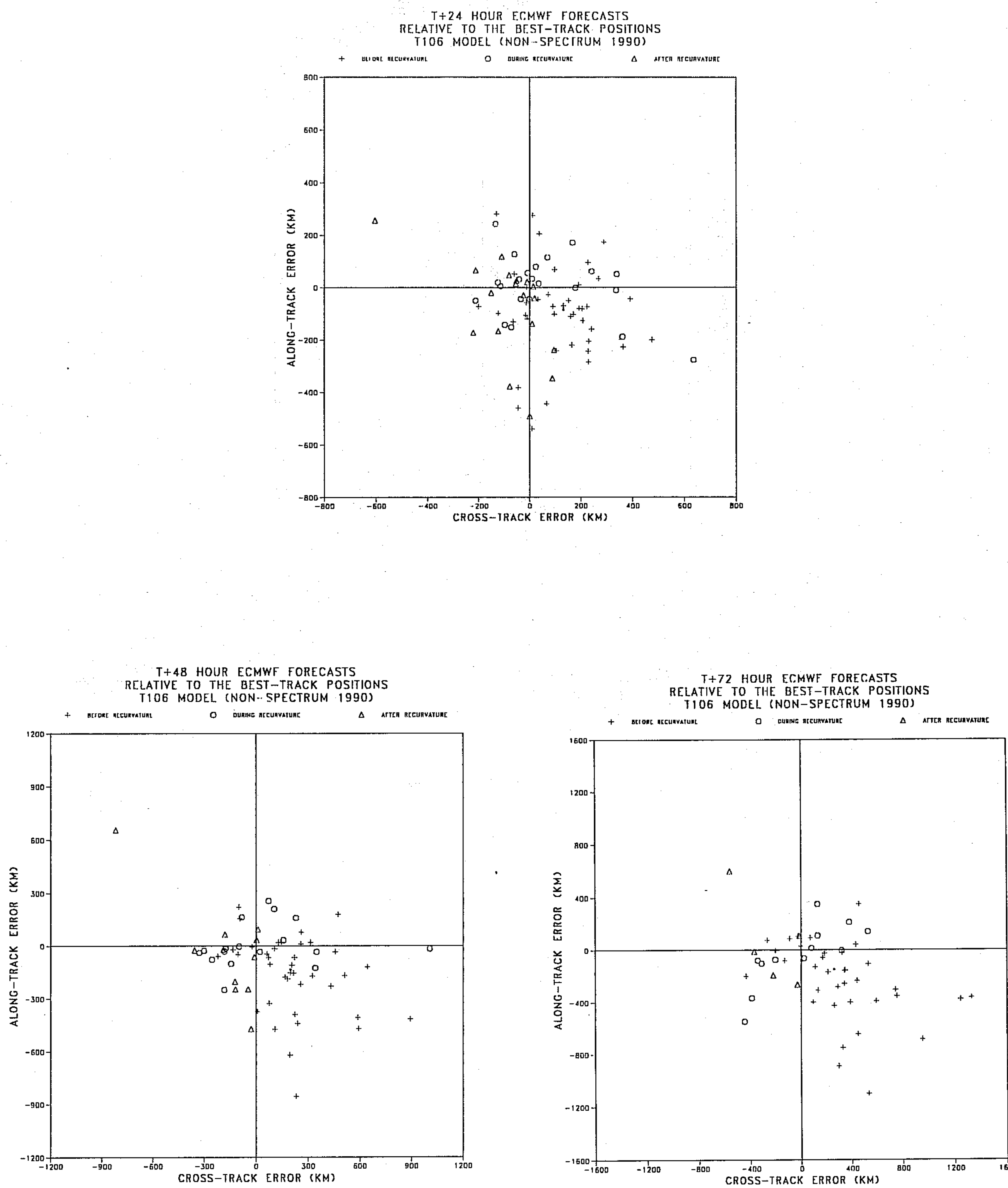


Figure 7 - ECMWF Forecasts Relative to the Best-track Positions for "T106 (Non-SPECTRUM 1990)"

(a) T+24 hours (b) T+48 hours (c) T+72 hours

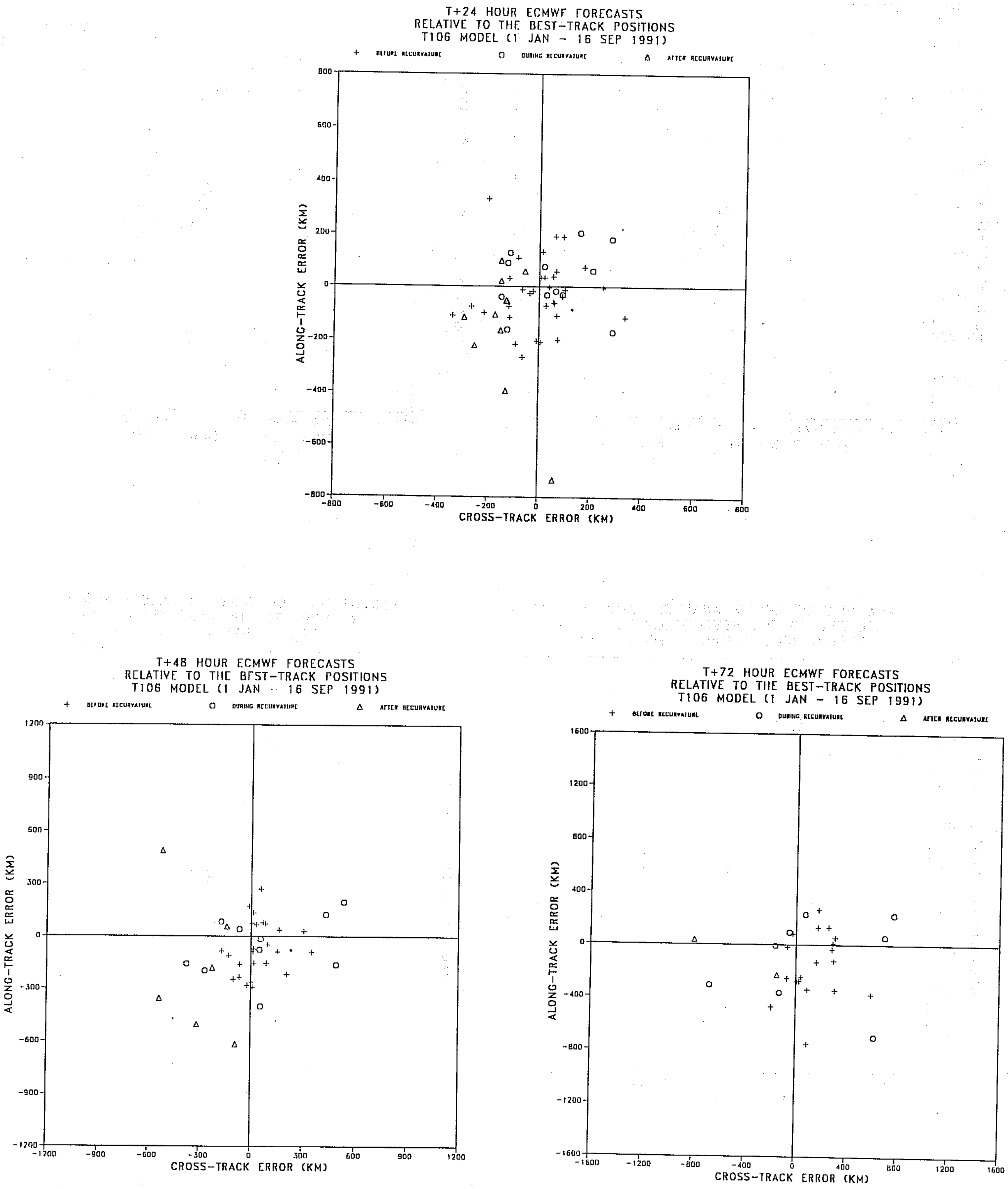


Figure 8 - ECMWF Forecasts Relative to the Best-track Positions for "T106 1991"

(a) T+24 hours (b) T+48 hours (c) T+72 hours

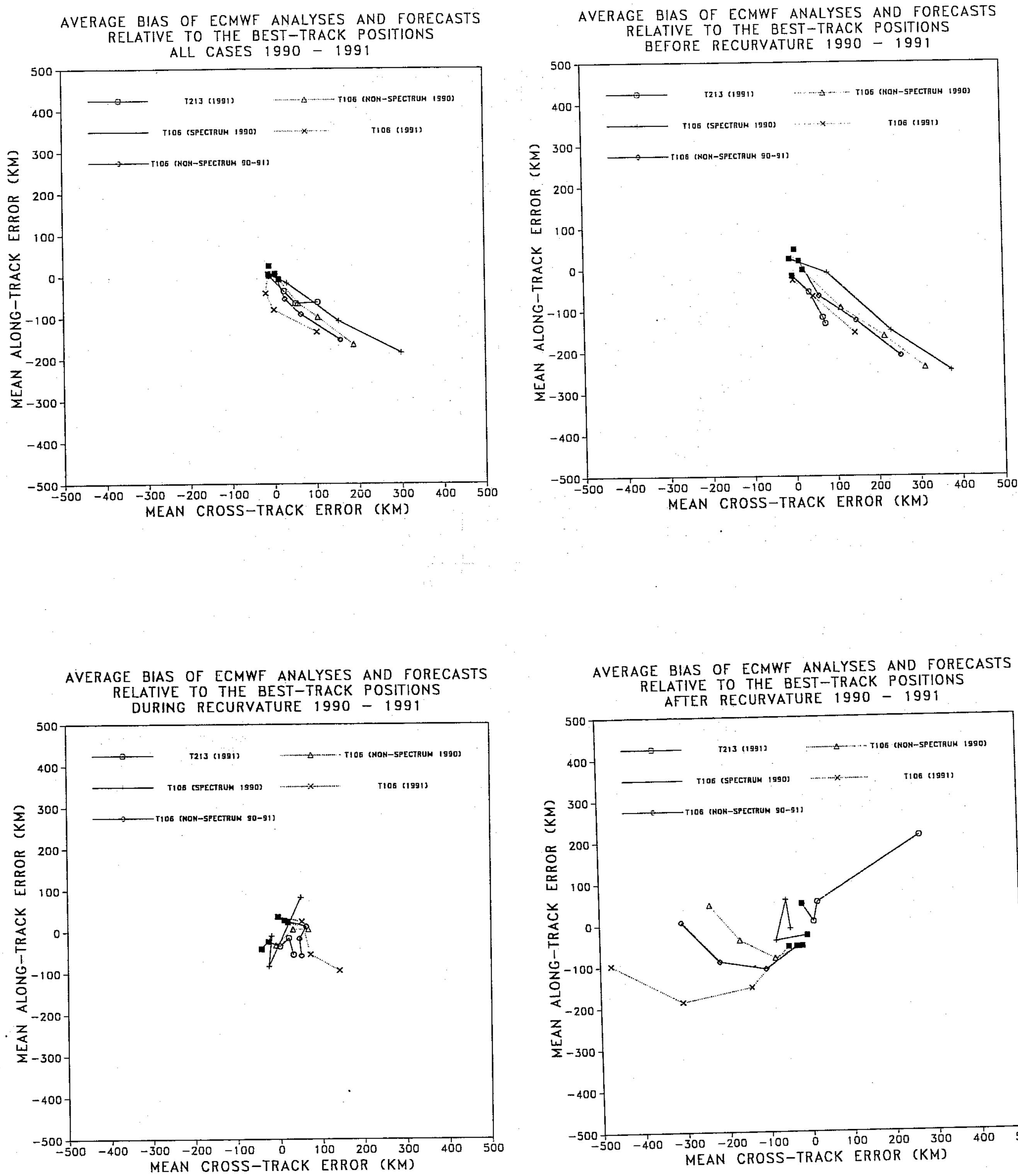


Figure 9 - Average Bias of ECMWF Analyses and Forecasts Relative to the Best-track Positions 1990-1991

(a) ALL Cases
(b) BEFORE Recurvature
(c) DURING Recurvature
(d) AFTER Recurvature

(Analyzed TC Positions Marked by Squares)

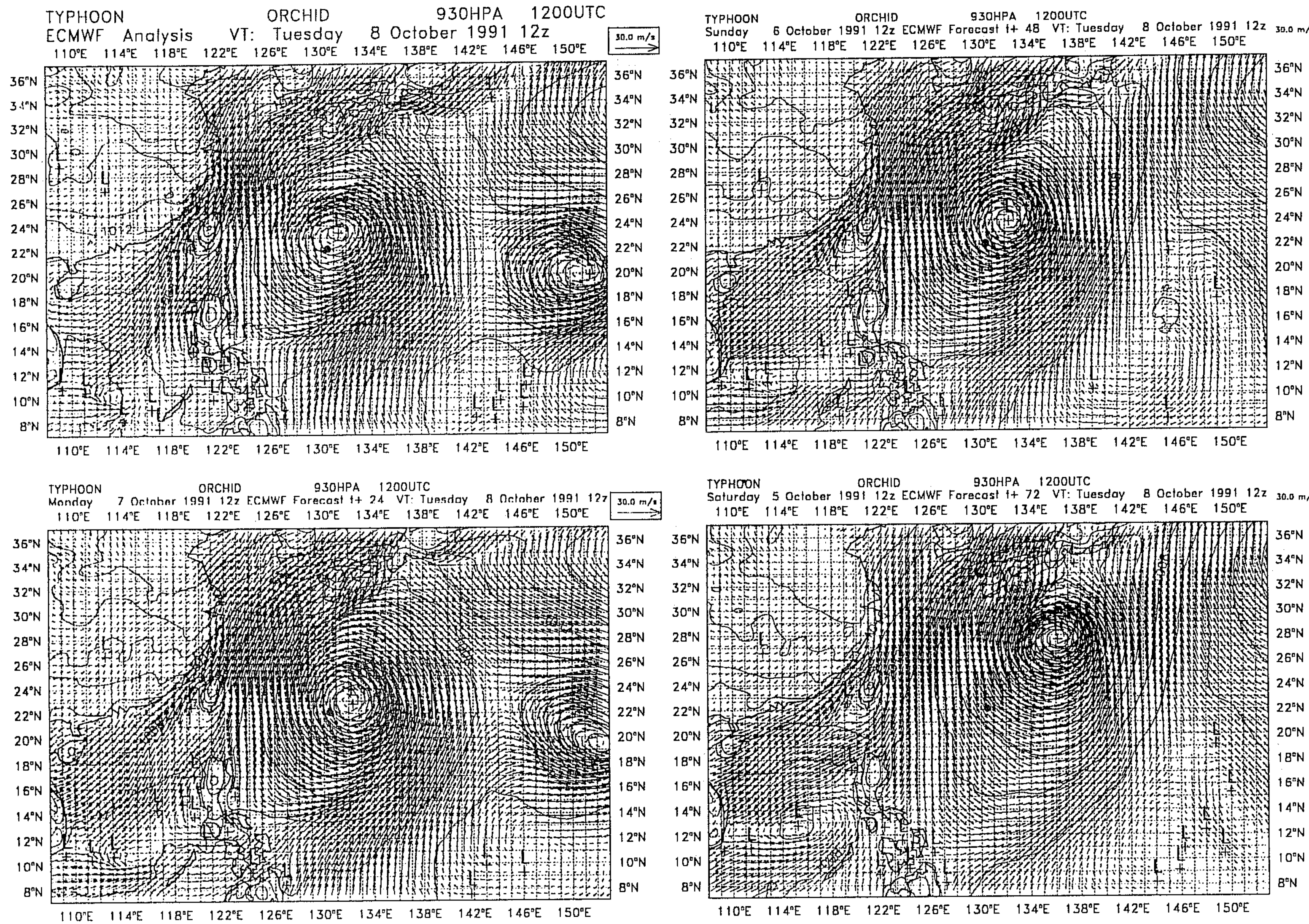


Figure 10 - T+24, T+48 and T+72 hour ECMWF TC Prognostic Charts Together with the Verifying Analysis for ORCHID, VT 8 October 1991 12 UTC (The black dot at the centre of each chart indicates the verifying best-track position)

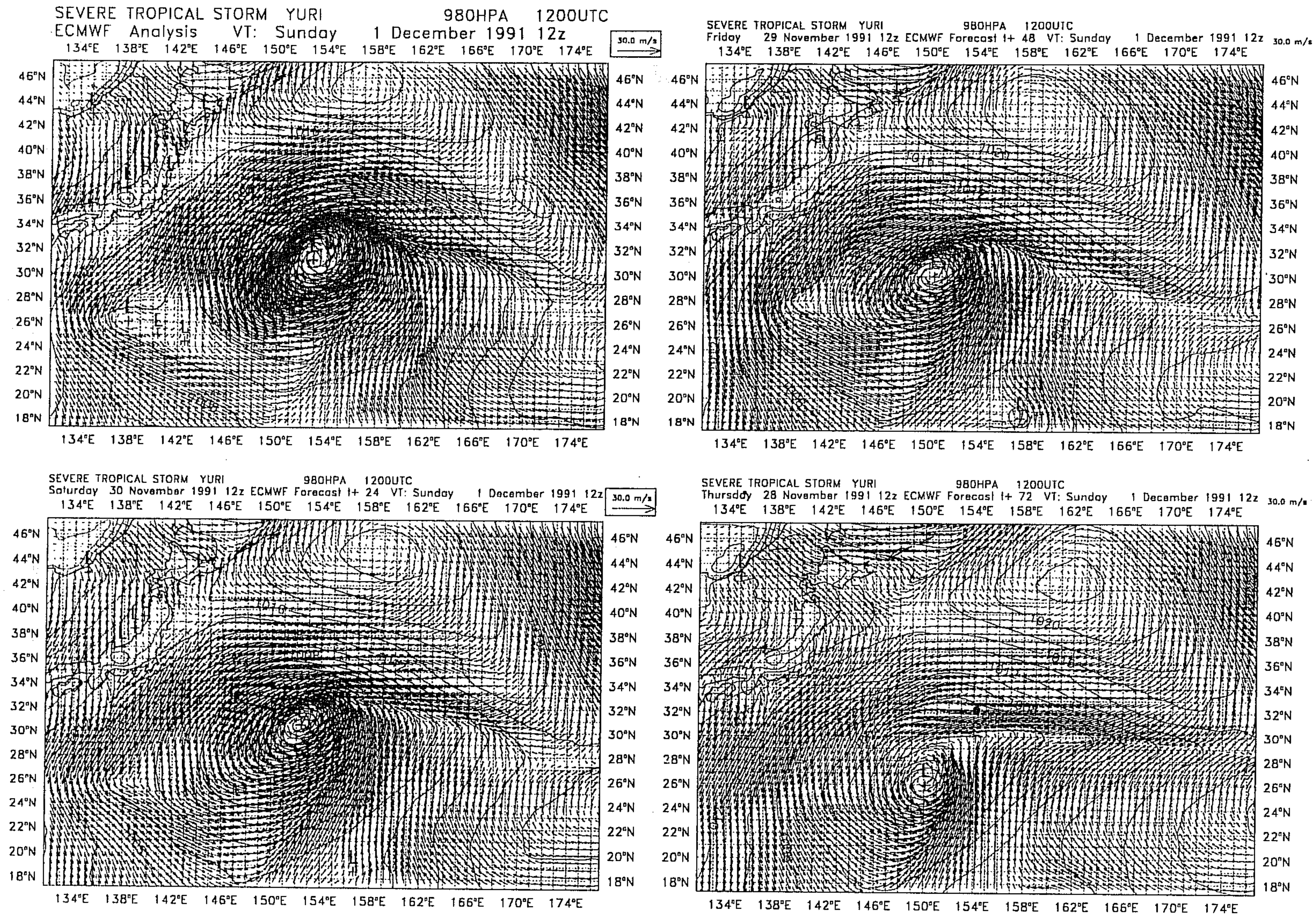


Figure 11 - T+24, T+48 and T+72 hour ECMWF TC Prognostic Charts Together with the Verifying Analysis for YURI, VT 1 December 1991 12 UTC (The black dot at the centre of each chart indicates the verifying best-track position)

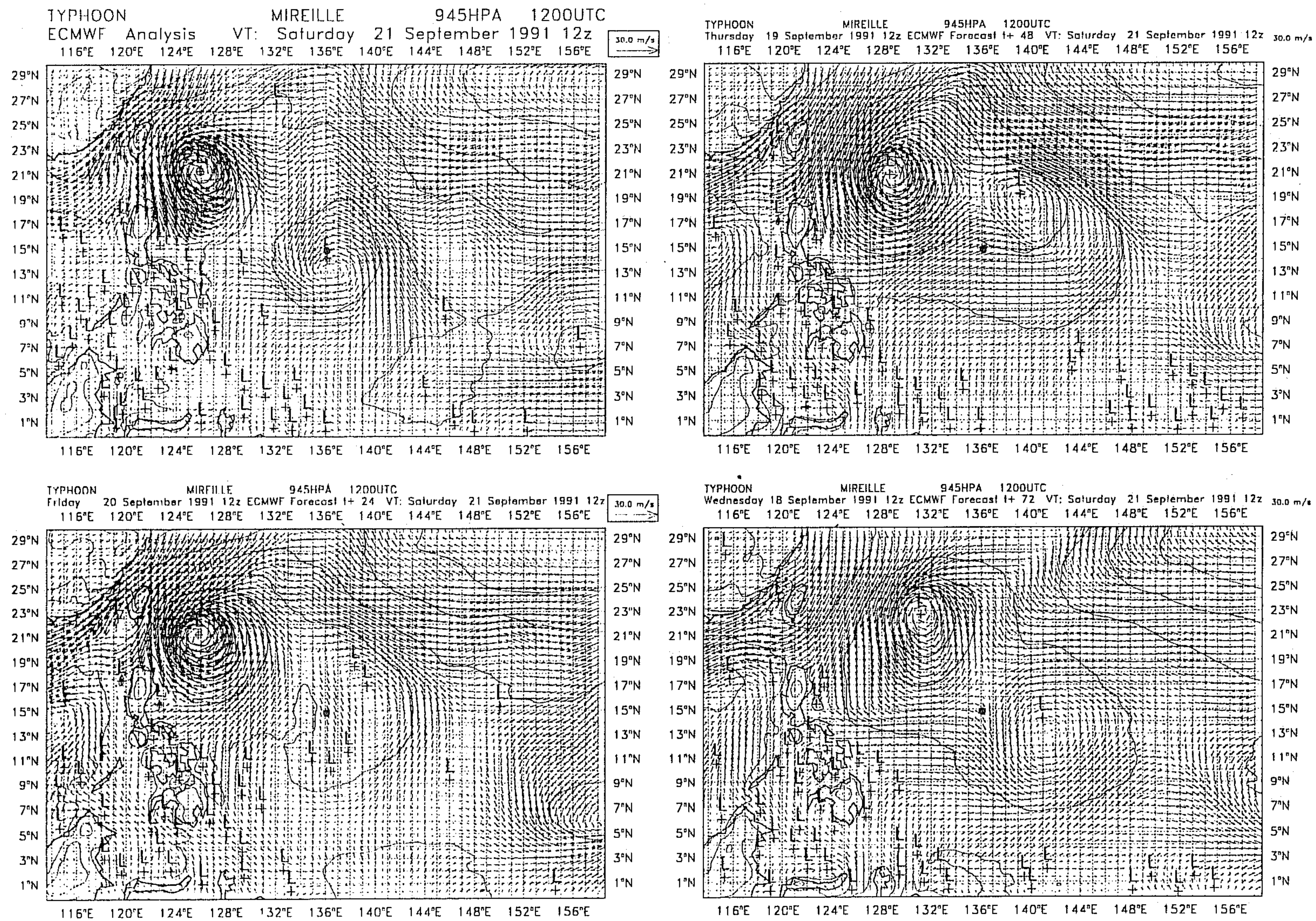


Figure 12 - T+24, T+48 and T+72 hour ECMWF TC Prognostic Charts Together with the Verifying Analysis for MIREILLE, VT 21 September 1991 12 UTC (The black dot at the centre of each chart indicates the verifying best-track position)

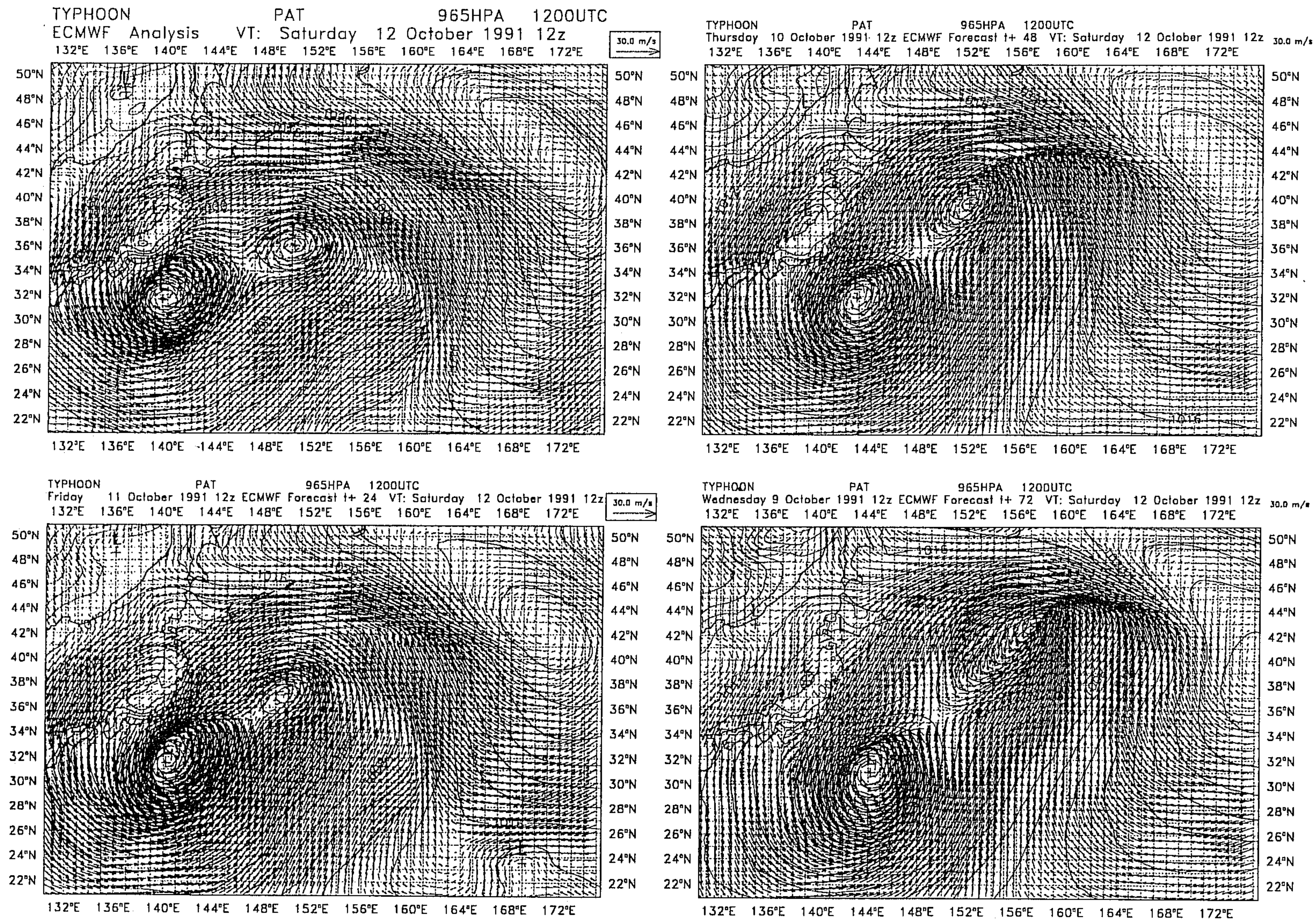


Figure 13 - T+24, T+48 and T+72 hour ECMWF TC Prognostic Charts Together with the Verifying Analysis for PAT, VT 12 October 1991 12 UTC (The black dot at the centre of each chart indicates the verifying best-track position)