Tellus (1985), *37A*, 297–308

Systematic errors in the behaviour of cyclones in the ECMWF operational models

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(Manuscript received December 27, 1983; in final form January 17, 1984)

ABSTRACT

Systematic errors in the forecasts (up to 10 days) of cyclones over the north Atlantic and Europe by the ECMWF operational grid point model (N48) for the 1981–82 winter seasons are described, and some corresponding results for the ECMWF operational spectral model (T63) for the 1983–84 winter season are shown. Statistics for the cyclone tracks, central pressure, deepening rates, etc., are given.

The forecasts from the grid point model tend to displace the cyclone tracks towards the south, especially after day 4, except near Newfoundland where a northward displacement is found. The corresponding errors are reduced in the spectral model. A systematic phase error is evident in the grid point model with the waves being too slow, usually in the developing stages of cyclones. This error is also apparent for the fast moving cyclones in the spectral model. For the grid point model, the forecast deepening and filling rates are less than those observed. However, the deepening rate is more realistic in the spectral model, though the filling rate is still underestimated. For both models the horizontal scale of the cyclones is too small during the first 2 or 3 days, especially in the forecasts started from several days prior to the day on which the cyclone was generated; during the later stages of cyclone development, the scale is too large. In comparing these errors to similar errors documented for other numerical models, some hypotheses are discussed about their likely causes.

1. Introduction

The best numerical models of today, the ECMWF operational models amongst them, have reached a very high level of accuracy and can now, in great detail, simulate the essential processes necessary for the prediction of extra-tropical cyclones (Bengtsson, 1981). Cyclones are important for local weather (precipitation, wind, thunderstorms, floods, etc.), especially on the lee side of mountain ranges, such as the Alps, Pyrenees and Taurus mountains in the southern part of Turkey. The central and eastern Mediterranean countries are influenced by the lee-cyclones of the Alps (Genoa-cyclones) during most of the winter months. Knowledge of cyclone tracks is also important for the routing of ships so as to minimize storm damage to both ships and cargo. A good short- to medium-range forecast of an intense vortex therefore helps to prevent loss or damage. Using climatological information alone is clearly insufficient (Motte, 1972).

In an earlier study of cyclones in the ECMWF forecasting system for the period September–October 1980 (Akyildiz, 1981), the predictability of the north Atlantic and European cyclones in the ECMWF grid point model was found to be quite high. The usefulness of the forecast reached up to day 5 or 6, even sometimes day 7. Similar results were found in recent studies of the spectral model. The main systematic error of the forecasts was a southward displacement of cyclones over the north Atlantic and northern Europe.

Girard and Jarraud (1982) investigated the differences between forecasts from a spectral and a grid-point model. There was evidence that (1) young cyclones move more quickly than mature ones in both models; (2) in the majority of cases, cyclones in the grid point model do not move as quickly northward as in the spectral model; (3) for slow-moving systems, both models are too fast, and finally, (4) for the fast-moving systems, both models are too slow.

Silberberg and Bosart (1982) found that in the NMC LFM-II model (a limited area fine mesh model with 127 km mesh length, higher horizontal resolution, but coarser vertical resolution than the ECMWF grid-point model), cyclones are forecast too slow in October and November and too fast in March and April, and had a reduced (slow) bias during December, January and February compared to October and November.

According to Leary (1971) and Sanders and Gyakum (1980), the operational six layer (6-L) and seven layer (7-L) primitive-equation models of NMC do not forecast storms deep enough over the oceans, and observed storms deepen faster and fill more slowly than their model counterparts (36 and 48 h forecast). These results agree with our findings, except for the filling rate of the model cyclones which are slower than those observed in the ECMWF operational models (N48, T63). Also, Leary (1971) and Sanders and Gyakum (1980) found that the northward curve of the NMC forecast track for the rapidly deepening cyclones is insufficient in the case of both models, (6-L) PE and (7-L) PE. The ECMWF grid-point model exhibits a similar tendency in forecasting cyclones tracks.

The purpose of this study is to identify systematic errors in the prediction of cyclones in the mean sea level pressure prognoses (up to 10 days) produced once daily from 12.00 GMT analyses by the ECMWF grid-point model (N48 i.e., 48 grid points between the equator and poles, i.e., 1.875° regular latitude/longitude grid), as well as by the ECMWF operational spectral model (T63 i.e. triangular truncation with maximum wave number 63, Baede et al. (1979)). The results may help to improve the forecasters' understanding, interpretation and use of the ECMWF forecasts, as well as to suggest avenues for future research.

In this paper, the emphasis is placed on results from the grid-point model, though some results from the spectral model will be shown and compared with those from the grid-point model. Therefore, the terms "forecast" and "analysis" will refer to the grid-point model unless otherwise stated. It should be pointed out that during the 1983–84 winter season, in which the spectral model was in operational use, the cyclones were less intense and had a shorter life cycle than those in the 1981–82 winter. This fact should be kept in mind when the two models are compared.

2. The ECMWF forecasting system

The ECMWF operational system before April 1983 was an intermittent data assimilation system consisting of a multivariate optimum interpolation analysis, a non-linear normal mode initialization and a high resolution grid-point model which produced a first guess forecast for the subsequent analysis. Data were assimilated with a frequency of 6 h. For a description of the data assimilation system, see Lorenc (1981).

The forecast integrations were performed with the operational ECMWF grid-point model, as described by Burridge and Haseler (1977) and by Tiedtke et al. (1979). Its basic features are summarized in Fig. 1 in Bengtsson et al. (1982).

From 21 April 1983, the spectral model (T36) and envelope orography has been implemented operationally at ECMWF. The T63 spectral model is based on a spherical harmonic projection with triangular truncation at wave number 63 (that means that the smallest wave resolved by the model has 63 maxima and minima around the equator). The resolution, due to the triangular truncation, is isotropic on the sphere; for more information see Baede et al. (1979).

3. Description of the study

For the purpose of this study, a cyclone is defined to be a low pressure centre surrounded by one or more closed isobars plotted at 5 mb intervals on the ECMWF forecast and verification charts. The life cycles of observed lows are separated into periods and compared with the verifying forecasts at the same time. This study covers three different periods. The main study is based on data from the 1981–82 winter season, though in the examination of the regional distribution of cyclones for the north Atlantic and European area, the winter of 1980–81 is included. The study of the results from the spectral model is based upon the 1983–84 winter season.

For the 1981–82 winter season, well-defined lows with sufficient enclosed isobars were selected. By plotting the central position of lows on a map during their life cycles up to D + 10 (the life cycle of very few cyclones exceeds 10 days) at 24 h time intervals, and connecting these positions, the observed track was constructed. A similar procedure was applied to corresponding lows in the forecasts which verify for the same period (see Fig. 1). Furthermore, the speed of cyclones, the cyclone central pressures, the geographical size of cyclones, and the life span of cyclones were also extracted from the forecasts and from the verifying analyses. If a cyclone falls on a boundary, it is recorded as belonging to the north/and or west adjacent box.

A similar study for the ECMWF operational spectral model during the 1983–84 winter season has been performed. Some results from this study will be discussed, and compared with the grid-point model in the following sections.

4. Results

4.1. Cyclone tracks

Figure 1 shows examples of the observed and predicted cyclone tracks, one from each month from December 1981 to February 1982. The dates on the tracks show the central position of the observed and forecast lows every 24 h during the life cycle of the observed lows. For example, on the observed and forecast tracks for December 1981, the figures of 20/12 indicate the central positions of the observed and forecast lows which verify at 12.00 GMT on 20 December 1981.

In Fig. 1, one can already see some of the systematic forecast errors in the cyclone tracks; for example, the forecast does not bend the track sufficiently far northwards; instead, it establishes a secondary superior track towards the continent of Europe. It is also evident that during the first 2 or 3 days, the forecast is too slow. These errors will be discussed in detail below.

Tracks which were oriented in the east–west direction were sorted according to whether the forecast track was to the left (north) of, to the right (south) of, or along the observed track (in a subjective way "along" means that a forecast track would land in a lane of approximately 200 km width centred on the observed track, see Table 1). The tracks were also sorted according to the days from which the forecasts were made, as well as by the periods of the life cycle of observed cyclones. Table 1 shows that for each stage of the forecast, the percentage with southward positions of the forecast track is greater than the percentage with northward positions. This difference increases with forecast period. For the first two days of the period, 50% of the forecast tracks were more-or-less along the observed track. The shift of the forecast track from the observed becomes significant from day 4 onwards. A summary of these results is given in the last row of Table 1, which indicates the weighted mean of cases (as percentages). According to the left-hand side of this table, of the 121

Table 1. *Cases sorted by position of forecast track: to the south (S), to the north (N), or along (M) the observed track; only cases in which the cyclones in the forecasts and in the verifying analyses show a tendency to move in an east–west direction have been included in this table*

	Forecast from analysis day D					Forecasts from one day earlier D − 1			
Forecast days	S	N	M	Sample size	Forecast days	S	N	M	Sample size
	%	%	%			%	%	%	
D + 1 and D + 2	25	19	56	52	D + 2 and D + 3	35	28	37	51
D + 3 and D + 4	41	32	27	44	D + 4 and D + 5	50	26	24	46
D + 5 and D + 6	64	12	24	25	D + 6 and D + 7	65	12	23	17
Weighted mean (%)	39	22	39	121	Weighted mean (%)	45	25	30	114

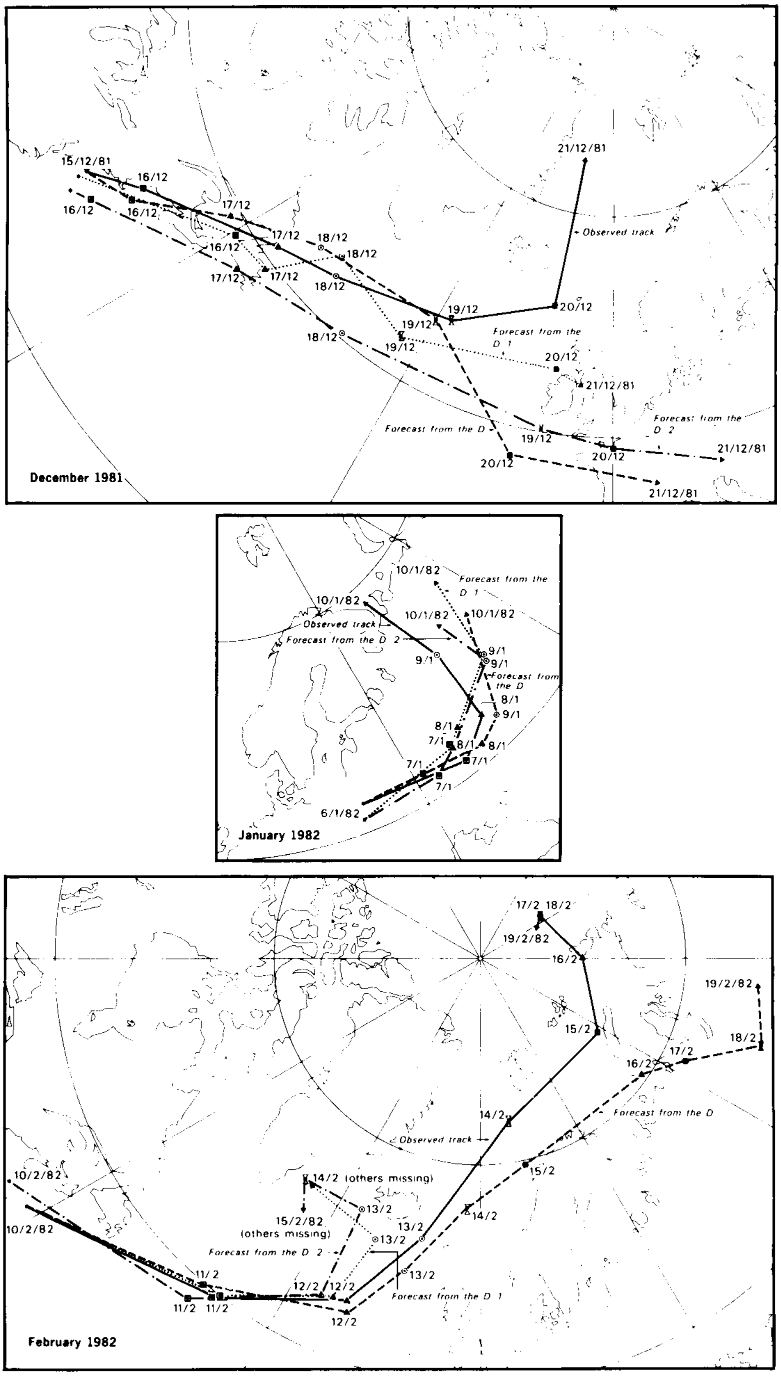

Fig. 1. Tracks of cyclones in the verifying analyses (——), in the forecasts from the day (D) on which the low was generated (– – – –), in the forecasts from the previous day D – 1 (· · · · ·), in the forecasts from 2 days earlier D – 2 (– · – · –).

forecast cyclones, 39% moved to the right (south) of the observed track, 22% moved to the left (north), and 39% moved more-or-less along the observed track.

Examining the forecasts from D − 1 (on the right-hand side of the table), we can see that of 114 tracks, 45% moved to the right (south) of the observed track, 25% moved to the left (north), and 30% moved along the observed track. Thus, the model has a systematic error of not bending the forecast track sufficiently northwards. The sample size from day 5 onward is rather small, but it confirms the trend seen in the earlier forecast days.

The spectral model is an improvement in the sense that the forecast tracks curve sufficiently northwards, but a similar tendency in the grid-point model is realized in the forecasts of the spectral model from D − 2.

4.2. Speed of cyclones

Systematic phase errors are examined by comparing the speed of observed and forecast lows. The mean speed of the lows in the forecasts and in the verifying analyses has been calculated for every 24-h interval. The calculation is only up to the 5th day of the life cycle of the observed low, while for the forecasts it is up to day 5 or 6, depending on whether the forecasts are from day D or from day D − 1. A graphical presentation of the cyclone speed is depicted in Fig. 2.

Figure 2 shows that while during the first 2 or 3 days of the forecast period, the model cyclones are too slow, in the later stages, their speed tends to increase. Thus, the model has a phase error with a tendency for observed lows to occur east of the forecast position on days 1, 2 or 3. This conclusion

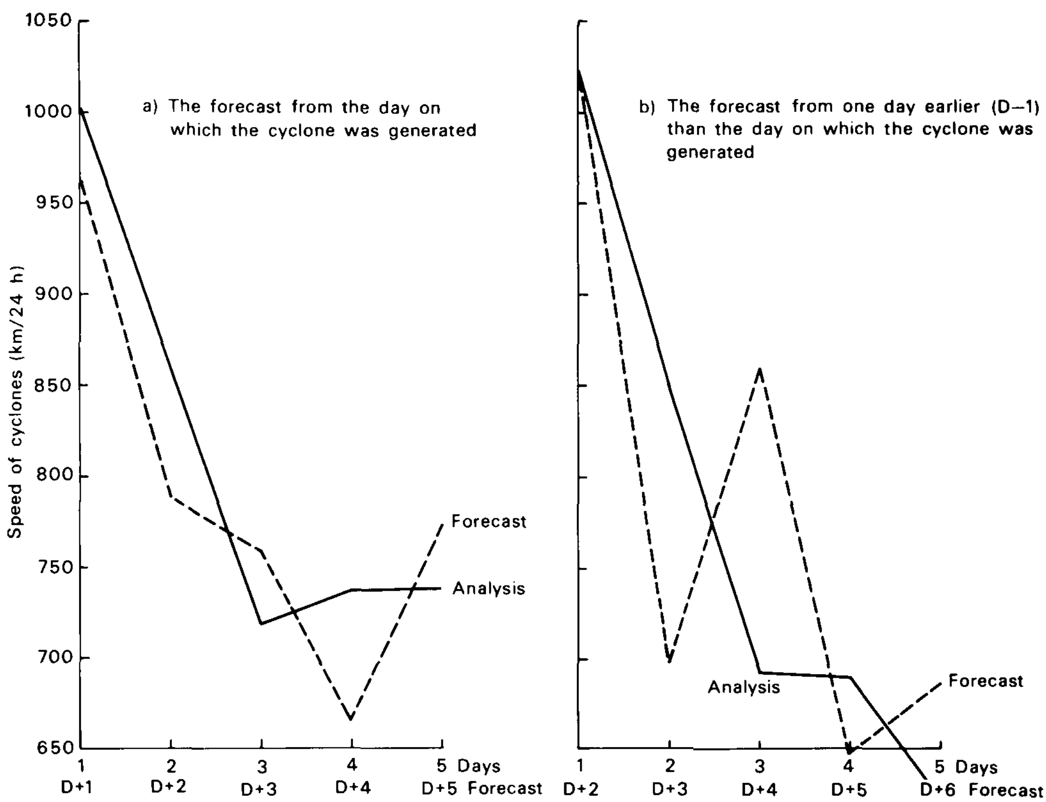

Fig. 2. Mean speed of cyclones in the forecasts (dashed lines), and in the verifying analyses (solid lines) (km/24 h). (a) The forecast from the day on which the cyclone was generated, (b) the forecast from one day earlier (D − 1) than the day on which the cyclone was generated.

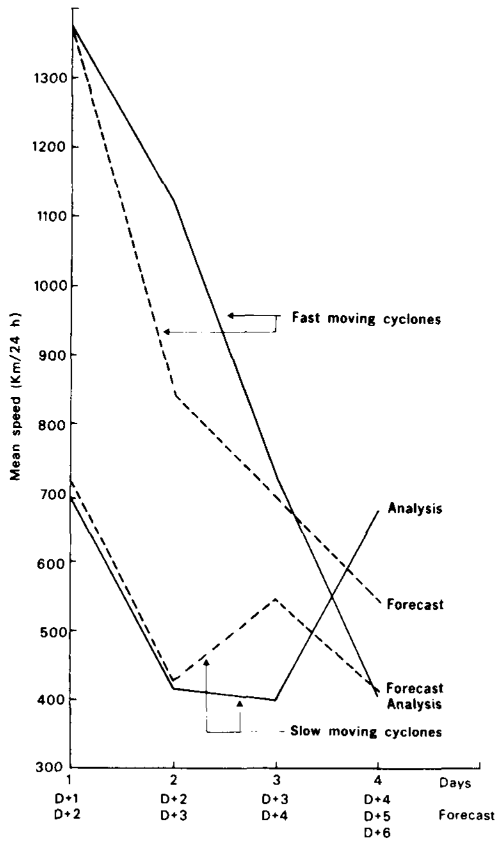

Fig. 3. Mean speed (EW component) of cyclones (spectral model). Forecast from the D and D − 1.

generally agrees with the results of Girard and Jarraud (1982) concerning the grid-point model.

Although the spectral model shows a similar tendency in the case of the phase error to the grid-point model, it is better than the grid-point, especially for slow-moving systems (see Fig. 3).

4.3. *Central pressure of cyclones*

The average central pressure, and the deepening and filling rates of cyclones in the forecasts and in the verifying analyses were compared in order to reveal systematic errors in the central pressure of forecast lows. This comparison had to be restricted to the first half of the forecast period, since only those cases in which the cyclones in both the forecasts and the verifying analyses reached the minimum central pressure at the same time (normally 1 or 2 days after generation) were taken into account. Therefore, conclusions derived in this section apply to the short-range forecasts, and may not be valid for forecasts longer than 4 days.

The central pressure of cyclones was estimated to within 2–3 mb. This is also an average error for the analyses' accuracy for normal developing lows; for lows which develop suddenly, it is expected to be within 5–6 mb. Figs. 4 (the forecasts were initiated from the day on which the cyclone was generated) and 5 (the forecasts were initiated from one day earlier than the day on which the cyclone was generated) depict the mean central pressure of the observed and the forecast lows. The left-hand sides of Figs. 4 and 5 show the results from the cases in which cyclones reach their minimum central pressure 24 h after the day on which the low was generated, i.e., cyclones which develop relatively rapidly. On the right-hand sides of the figures, the cyclones which reach their minimum central pressure 48 h after the day on which the low was generated, have been included, i.e., cyclones which develop relatively slowly. It can be seen from these figures that in the cases of rapidly growing cyclones, the model lows deepen less than those observed.

The deepening rate for both forecast and observed lows is defined as the difference between the central pressure of the low centre at the initial time and the value 24 h later. Table 2 shows a contingency table of 90 cases where the deepening rates are divided into categories depending on the combination of forecast deepening rate and observed deepening rate. Only the cases with zero or positive values (initial central pressure − verified central pressure) have been taken into account. This table shows that, on average, the forecast deepening rate is less than that observed. Thus, according to Figs. 4 and 5 and Table 2, the overall impression is that the rapidly developing lows deepen faster in reality than the model predictions. In other words, the deepening of the central pressure of the model cyclones is delayed during the first 24 and 48 h.

Similarly, the forecast filling rate (for forecasts from day D, day D − 1 and day D − 2) and the observed filling rate have been calculated, and compared with each other in Table 3. The filling rate is defined as the difference between the minimum central pressure of the low centre and that 24 h after the time at which the low centre reached its minimum pressure. The cases chosen here are those for which the lows in the forecasts

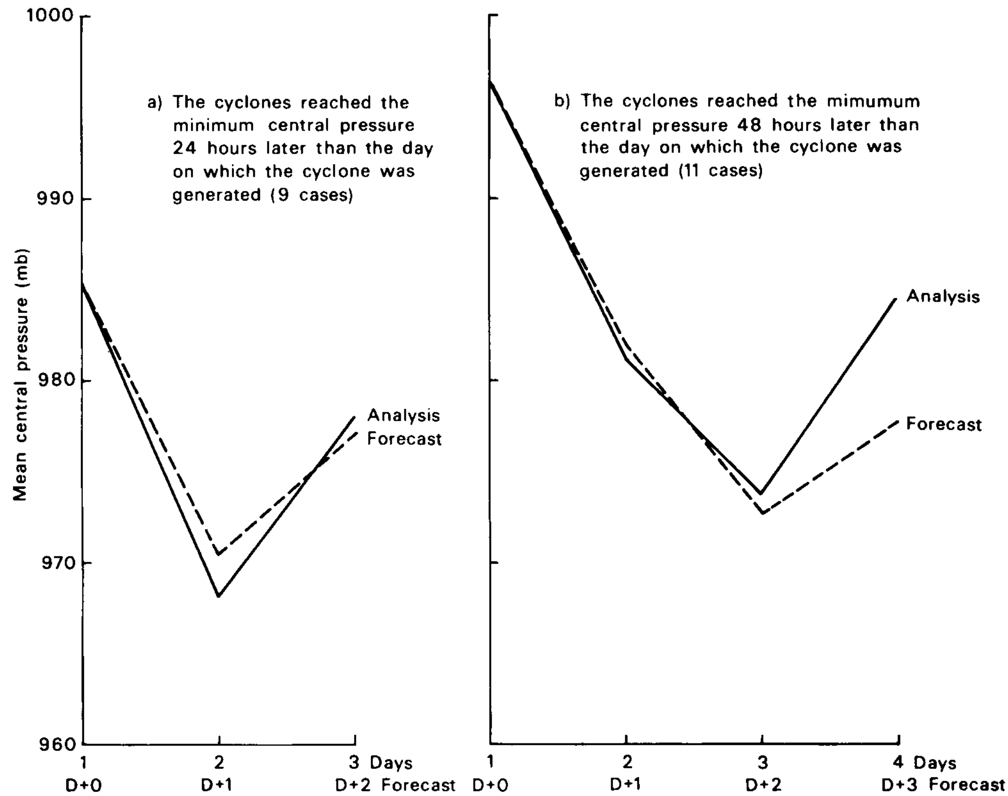

Fig. 4. Mean central pressure of cyclones in the forecasts (dashed lines), and in the verifying analyses (solid lines). The forecasts were initiated from the day on which the cyclone was generated; (a) the cyclones reached the minimum central pressure 24 h later than the day on which the cyclone was generated (9 cases); (b) the cyclones reached the minimum central pressure 48 h later than the day on which the cyclone was generated (11 cases).

Table 2. *Cyclones sorted out by forecast deepening rate (initial central pressure – verified central pressure) and observed deepening rate of cyclones (both in mb/24 h); N = 90*

	Forecast deepening rate					
Observed deepening rate	0 ≤ 7	+8 ≤ 7	+16 ≤ 23	+24 ≤ 31	+32 ≤ 39	+40 ≤
0 ≤ 7	12	6	1			
+8 ≤ 15	5	14	3			
+16 ≤ 23	2	15	13	1		
+24 ≤ 31		2	4	3		
+32 ≤ 39				2	1	
+40 ≤				4	2	

N = sample size.

and in the verifying analyses reached the minimum central pressure simultaneously. Table 3 shows that, on average, the forecast filling rate is less than the observed rate, that is, the observed lows fill faster than the model predicts. Thus we see that the model neither deepens nor fills lows as quickly as in reality.

The deepening rate of the model lows in the T63 forecasts have improved, but the filling rates for the spectral model are similar to the grid-point model,

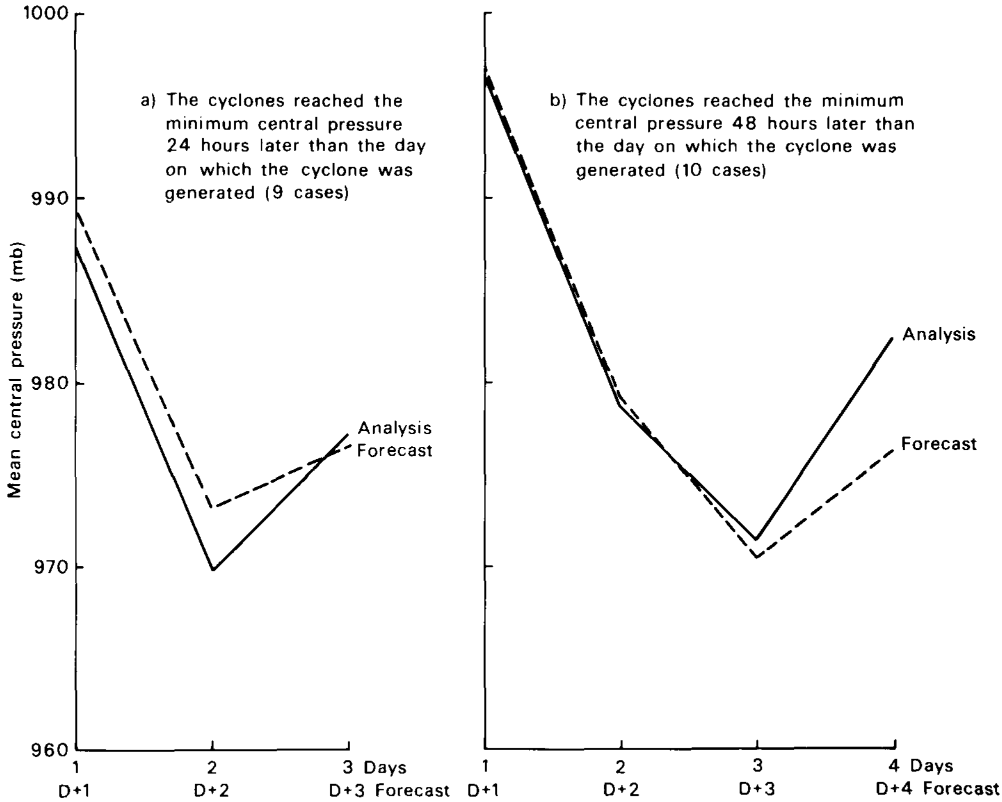

Fig. 5. As Fig. 4, but the forecasts were initiated from one day earlier than the day on which the cyclone was generated, (a) (9 cases), (b) (10 cases).

Table 3. *Cyclones sorted by observed filling rate (minimum central pressure – central pressure 24 h later) and forecast filling rate in verifying forecasts against analyses (both in mb/24 h); N = 65*

	Forecast filling rate				
Observed filling rate	0 ≤	+5 ≤	+10 ≤	+15 ≤	+20 ≤
0 ≤	6	5	1		
+5 ≤	6	8	2		1
+10 ≤	10	8	5	2	
+15 ≤	4	2	2	1	
+20 ≤			2		

N = sample size.

that is, the forecast lows fill slower than the observed.

4.4. *Magnitude of cyclones*

The magnitudes of cyclones, i.e., the geographical area enclosed by the largest closed contour, in the forecasts and verifying analyses were subjectively compared to identify systematic errors. Cases were sorted according to whether the forecast low was larger than the observed low, or vice-versa, and by the forecast period; the results are shown in Table 4.

Table 4 shows that in general, the model cyclones

Table 4. *Number (%) of cyclones in forecasts (F) which are greater than, less than or equal to those analysed (A) in magnitude; D is the day on which the cyclone was generated*

Forecast from	Forecast period								
	D + 1 and D + 2			D + 3 and D + 4			D + 5, D + 6 and D + 7		
	$A < F$	$F < A$	$F = A$	$A < F$	$F < A$	$F = A$	$A < F$	$F < A$	$F = A$
day D	12	17	49	20	17	29	9	4	18
	(15)	(22)	(63)	(30)	(26)	(44)	(29)	(13)	(58)
day D − 1	4	22	50	22	18	26	16	8	18
	(5)	(29)	(66)	(34)	(27)	(39)	(38)	(19)	(43)
*day D − 2	2	7	22	8	19	36	26	9	21
	(6)	(23)	(71)	(13)	(30)	(57)	(46)	(16)	(38)

* There is no day D + 1 forecast from the D − 2.

Table 5. *Number (%) of cyclones in forecasts (LF) which are greater than, less than or equal to those analysed (LA) in life span; D is the day on which the cyclone was generated*

Forecast from	LA < LF	LF < LA	LF = LA	Sample size
day D	18	4	16	38
	(48)	(10)	(42)	
day D − 1	16	11	11	38
	(42)	(29)	(29)	

are smaller than those observed during the first 2 or 3 days of the forecast period, whereas during the later stages of the forecasts, there is a tendency for the reverse to happen. This is in keeping with the result of subsection 4.3, i.e., that the model is slow in both deepening and filling depressions.

With regard to the magnitude of the cyclones, the spectral model shows a very similar tendency to the grid-point model.

4.5. The life span of cyclones

The time period between the cyclogenesis stage and the cyclolysis (relative age up to one day before the day on which the closed isobars of the cyclone vanish) stage of a cyclone is defined as the life span of that cyclone. The life span of the cyclones in the forecast (from day D and from day D − 1) and in the verifying analyses were compared (see Table 5).

For the forecasts from day D, Table 5 shows that 42% of observed and forecast cyclones have the same life cycle (i.e., decayed on the same day). However, for the forecast from D − 1, this figure is reduced to 29%. On the other hand, almost half the forecast cyclones had longer life spans than the observed lows. Thus, in the model, cyclone decays usually occur too late.

The spectral model also delays the decay of cyclones.

4.6. Regional distribution of the cyclones for winter months 1980/81–1981/82 and for winter months 1983/84

For the winter months of 1980/82, the number of cyclones in the forecasts (D + 5 and D + 10) and in the verifying analyses have been counted in 5 × 10 degrees latitude–longitude grid boxes in the area 30° N to 70° W, 80° N to 50° E. The numbers were plotted at the centre of the respective areas and isopleths drawn. The results are shown in Fig. 6. This shows that both predictions (D + 5 and D + 10) underforecast the occurrence of Mediterranean cyclones over the eastern Mediterranean, and also underforecast the cyclones in the Norwegian Sea, whereas the number of cyclones over western and eastern Europe was overestimated by the forecasts. Cyclones south of Newfoundland were shifted too far north in both forecasts. The main track of the cyclones from Newfoundland towards the north of Norway, which is very similar to the mean primary track shown by Motte (1972), was well captured by the D + 5 forecasts; however, a significant southward shift of this track is notable in the D + 10 forecasts. Both forecasts missed the cyclonic activity near

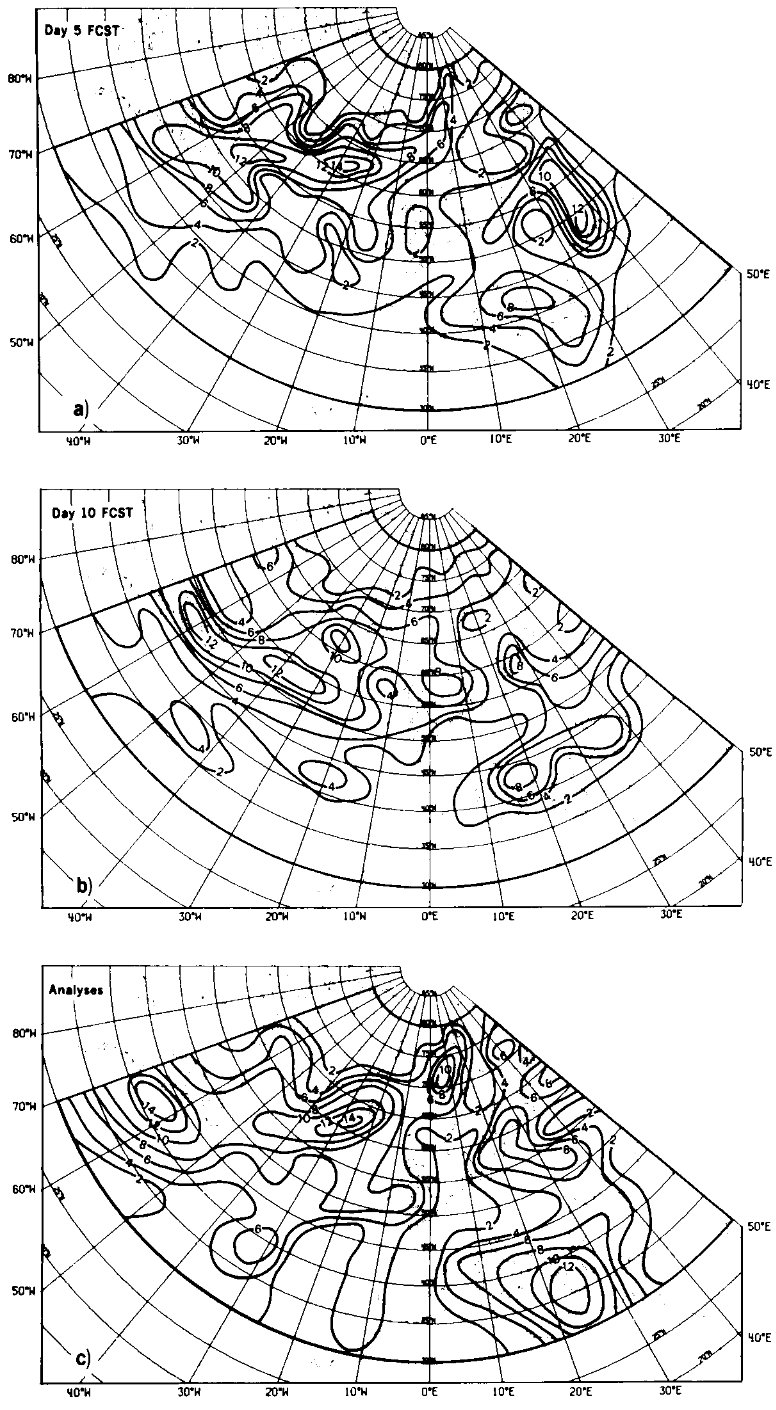

Fig. 6. Number of cyclones at surface in 5° latitude by 10° longitude for areas: (a) for 5-day forecasts; (b) for 10-day forecasts, (c) for verifying analyses, for the winter months 1980–81 and 1981–82.

Madeira, southwest of the Iberian peninsula, and in the southern parts of the mid-Atlantic.

A similar study was performed for the spectral model for the period November 1983 to February 1984. This showed that the deficiencies in the number of forecast cyclones over the central and eastern Mediterranean, and the shifting of the model cyclones northeast towards the Black Sea are common errors in both the spectral and grid-point models; also both models overpredicted the number of cyclones over Europe.

5. Discussion and conclusion

The ECMWF surface pressure forecasts by the 15-layer, N48 grid-point and T63 spectral models show several systematic errors with respect to tracks, central pressures and positions of cyclones. The results show that there is a southward shift of the main Atlantic storm track, and a northward displacement of the model lows near Newfoundland (see Fig. 6). After day 4, a southward displacement of the forecast track from the observed is significant. This behaviour is related to the fact that the ECMWF models, as with most general circulation models, tend to forecast a flow which is more zonal than it should be (Hollingsworth et al., 1980; Derome, 1981; Wallace et al., 1983; Arpe, 1983). Figs. 2 and 3 show that during the first 2 or 3 days of the life cycle of the lows, the speed of the forecast lows, especially for the fast moving cyclones, is slower than that observed. This error is likely to be due to the resolution and the associated truncation error of the model (Girard and Jarraud, 1982).

Short-range forecasts (i.e. up to day 4) on the average, underestimate both the deepening rate and the filling rate of lows (see Tables 2 and 3). The error in the forecast deepening rate of cyclones might increase if we take into account that the analyses tend to underestimate central of lows, particularly when they are rapidly developing. The forecasts from both models generally show a tendency to produce lows that are smaller in horizontal scale than observed at the beginning of the life cycle, and larger towards the end. Similar results have been found by comparing the life span of cyclones in the forecasts and in the verifying analyses, and their deepening and filling rates. According to this comparison, almost 50% of forecast lows have a longer life span than those observed, i.e., the forecast lows decay too slowly in the models which are also marginally slow in deepening the very rapidly growing systems (N48 only). The error in the horizontal scale, and in the life span of the model lows can be related to the deepening and filling errors. An experiment (one case only) by Simmons (1981) showed that this type of error is mainly related to the still comparatively low resolution of the model (N48). Unsatisfactory parameterization of moist processing is also a possible candidate for explanation of differences in filling rates. However, Sanders and Gyakum (1980) suggest that further improvement in the forecast deepening rate cannot be achieved by increasing the horizontal resolution.

According to them, the main causes of the systematic error in the NMC operational models (6-L and 7-L PE) are the inadequate representation of the bulk effects of cumulus convection and the planetary boundary layer, and the inadeuate vertical resolution.

Furthermore, Leary (1971) indicated that the smoothed topography of the operational six-layer primitive equation model of NMC may cause the forecast lows to be too deep over land, especially near mountains; the enhanced orography (envelope) of ECMWF did not prevent the model from over-deepening the cyclones over the continent. This leads us to suspect that some other effects, such as deficiencies in the treatment of land/sea thermal contrast, or the remaining inadequacies of the treatment of orography, may be responsible.

For the spectral model, the filling rate is similar to that for the grid-point model, but the deepening rate is reasonably good. The error in the filling rate for both models of the ECMWF is inconsistent with the result of Leary (1971).

An inadequate representation of the Alps in the ECMWF grid-point model is most likely responsible for the underestimation of cyclonic activities in the forecasts, D + 5 and D + 10, over the Mediterranean (see Fig. 6, Tibaldi and Buzzi 1982). This is due to the fact that a very "smooth" topography was used in the operational model until April 1981; even the improved orography inserted in April 1981 (Tibaldi, 1982) still leads to an underestimation of the cyclogenetic effects of the Alps (Dell'Osso and Tibaldi, 1982).

Although an envelope-type orography is used with the spectral model, some deficiencies in cyclonic activity over the Mediterranean are still present in the model behaviour. The systematic error of the NMC hemispheric primitive equation model is characterized by a progressive weakening of the meridional temperature gradient and the land-sea thermal contrast with increasing forecast interval, and a weakening of the stationary wave pattern, both in the mid-troposphere and at the earth's surface (Wallace et al., 1983).

Nevertheless, the similarity of the spectral and grid-point models with respect to their inability to maintain the stationary wave pattern, is interesting and perhaps suggestive of common deficiencies in the model formulation (Wallace and Woessner, 1981).

6. Acknowledgements

I thank Drs. Arpe, Tibaldi, Grønås, Woods, Riddaway, Speth and Böttger for their suggestions and helpful discussions and also thank Mr. R. Hine and Mrs. Williams for the artwork.

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