Skill of Operational Dynamical Models in Cyclone Prediction Out to Five-Days Range during ERICA

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ABSTRACT

Investigating the skill of prediction of surface cyclones by operational models to ranges of five days, we studied the central and western North Atlantic region for the December 1988 through February 1989 period of the Experiment on Rapidly Intensifying Cyclones over the Atlantic (ERICA). Output was evaluated from the medium-range forecast (MRF) model of the National Meteorological Center (NMC) and (as available) from the models of the United Kingdom Meteorological Office and the European Centre for Medium-Range Weather Forecasting. Operational manual NMC analyses were used for verification.

For the MRF model, the correlation coefficient between predicted and analyzed 24-h deepening or filling was 0.91 for day 0–1, decreasing to 0.57 for day 4–5. There was little bias. The other models yielded lower values at a given range, with an underestimate of deepening.

Explosive deepening was identified by all three models at all ranges with at least small skill, on the basis of the Conditional Success Index. Scores for the MRF model were higher for a given range than for the other models.

Position error for the MRF model was about 150 km in the initial analysis. In the forecast it grew linearly at the rate of about 125 km per day. Errors in the other models were slightly larger at a given range.

The MRF model performed decidedly worse in the eastern Pacific region than in the Atlantic area during the same period.

At 500 mb at 40°N, 65°W, the day-to-day height changes were somewhat better predicted by the MRF model than by the others, but different results were found at other selected points.

The MRF guidance was used with considerable success by the ERICA forecasters in making operational decisions.

1. Introduction

Studies of medium-range or extended-range forecasts have used pattern anomaly correlation or rms forecast geopotential error as measures of accuracy and skill, applied globally (Kalnay et al. 1990; Palmer et al. 1990a; Roads 1989) or regionally (Chen 1990; Palmer et al. 1990b), or to a large-scale disturbance in the flow (Tracton 1990). Studies of smaller-scale individual cyclones, anticyclones, and mobile upper-level troughs, on which the weather of a specific day so strongly depends, have been restricted to forecast ranges of about two days (Smith and Mullen 1991; Mullen and Smith 1990; Alexander and Young 1990; Grumm and Siebers 1989a,b; Sanders and Auciello 1989), evidently on the tacit assumption that little skill would be found at medium ranges. This skepticism is reinforced by a recent study (Livingston and Schaefer 1990) of anomaly correlations for specific wavenumber bands in medium-range forecasts.

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An opportunity and a necessity to test this assumption arose during the field phase of the Experiment on Rapidly Intensifying Cyclones over the Atlantic (ERICA) from December 1988 through February 1989 (Hadlock and Kreitzberg 1988)—an opportunity because of the exceptionally good data coverage (Sanders 1990), and a necessity because of the long lead time for initial decisions concerning intensive observational periods (IOPs). These decisions were based in large measure on the medium-range forecast (MRF) runs of the National Meteorological Center's (NMC's) global spectral model (Kanamitsu 1989), as available on the Automation of Field Operations System (AFOS) at NMC and at other National Weather Service offices. Some reference was made also to forecasts received at NMC from the global models of the United Kingdom Meteorological Office (UKMO) and the European Centre for Medium-Range Weather Forecasting (ECMWF).

In this investigation we study the performance of these models in the western and central North Atlantic regions during the ERICA period. For further evaluation of predictive capability, we also examine the performance of the MRF in the eastern North Pacific region during the same period.

2. Broad-scale aspects

An outline of the behavior of the planetary-scale circulation during the three-month period is presented in Fig. 1. It represents the weekly average configuration of the main belt of 500-mb westerlies, and shows the tracks of some of the surface cyclones included in the study.

For the first half of December, Fig. 1 shows a trough over the western Atlantic and the east coast of North America, with heights lower than the long-term average. A major ridge lay along the west coast of North America and a pronounced trough was seen in the east-central Pacific area. This pattern is consistent with the positive phase of the Pacific/North America (PNA) mode of low-frequency variability (Wallace and Gutzler 1981), and with the ridge–trough (RT) pattern shown by Smith and Mullen (1991). Vigorous surface cyclogenesis occurred in the ERICA region south of 40°N, and the first three IOPs fell in the later part of this period.

In the last half of December, the western Atlantic trough filled as this pattern gave way to more zonal flow with positive height anomalies over the westernmost Atlantic and a trough in western or central North America. This regime resembles the trough–ridge (TR) pattern shown by Smith and Mullen (1991). Surface cyclone tracks (with a single exception just prior to the change of regime) lay farther north.

The first week in January was again very active in the ERICA region, with a broad 500-mb trough over the central and western Atlantic and three intense surface cyclones in rapid succession. The last of these prompted ERICA IOP 4 and attained a singularly low central pressure for an extratropical storm in such a low latitude (Nieman et al. 1991).

The PNA-positive, or RT, pattern did not return during the remainder of the period of study (Fig. 1), and weekly 500-mb heights were above the long-term

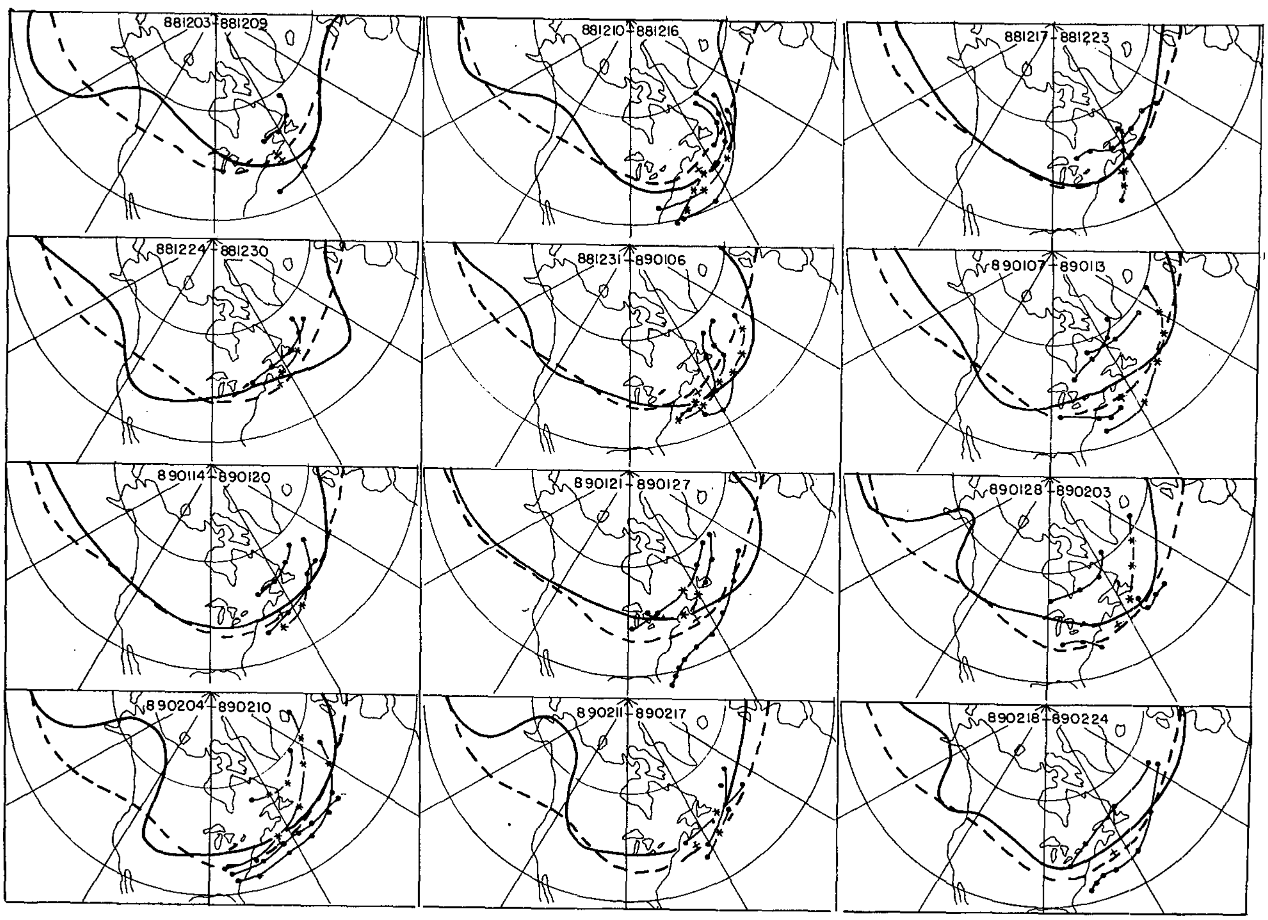

FIG. 1. Subjectively estimated mean position of the 552-dam contour of the 500-mb level for each of 12 weeks during December 1988–February 1989. The dashed line represents the long-term mean position of the contour for the week. Tracks of surface cyclones over the Atlantic are shown by 12-h segments. An asterisk indicates that the time was the middle of a 24-h period of explosive deepening. Cross-hairs indicate the location of 40°N, 65°W.

mean value over the ERICA region, with strong zonal flow. Surface cyclone tracks covered a broad range of latitudes, but explosive intensification tended to occur north and east of the main ERICA observational area (apart from the IOP 5 storm during the third week in January).

Amplitudes of the planetary ridges and troughs were weak after mid-December until almost the end of January (Fig. 1). Then a massive ridge appeared suddenly over Alaska and dominated the eastern Pacific area through the following month (Tanaka and Milkovich 1990). This event was poorly predicted by all three models but had little obvious impact on surface events over the Atlantic in the real atmosphere. It occurred, however, during a two-week period of extremely poor model forecasts at 500 mb, as will be seen.

After mid-December the 552-dam contour in the eastern Pacific region was generally poleward of its long-term mean position, although anomalously cold air dominated Alaska during January (Tanaka and Milkovich 1990). Blocking was prevalent in the Gulf of Alaska throughout February.

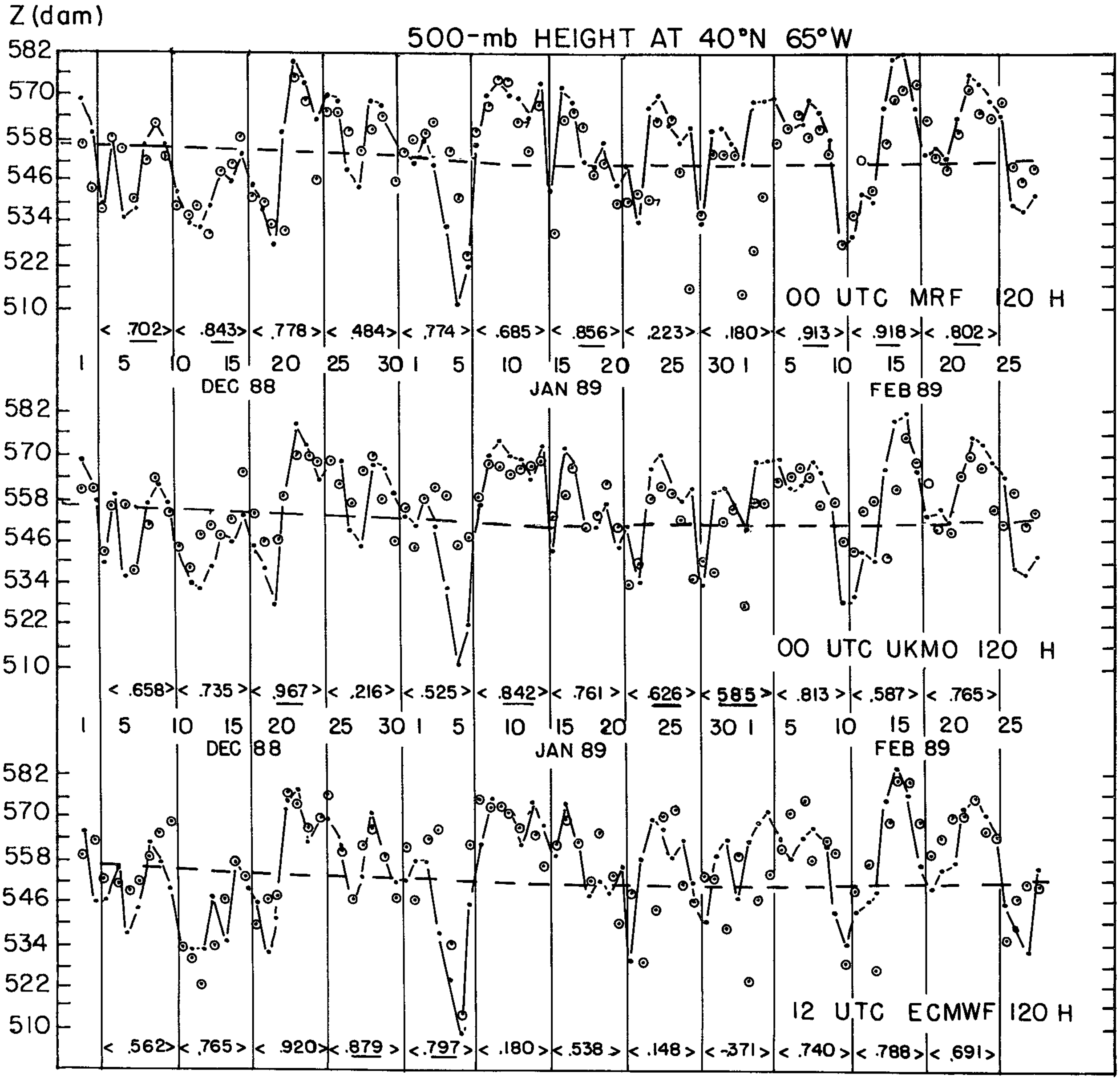

FIG. 2. Time series of 500-mb heights (dam) at 40°N, 65°W from 3 December 1988 to 24 February 1989, as given in the MRF initial analyses. Dashed lines indicate the long-term mean. Circled dots indicate 120-h forecast values verifying at 0000 UTC for the MRF (top) and UKMO (middle) runs, and at 1200 UTC for the ECMWF runs (bottom). Seven-day correlations for each individual week are shown for each model, with the underline indicating the weekly winner.

3. 500-mb height forecasts

The daily behavior of the 500-mb height at 40°N, 65°W, a point representative of the major western Atlantic surface cyclogenetic area of concern to ERICA, is illustrated in Fig. 2. The height in the initial MRF analysis is shown, along with 120-h forecasts of that height as produced by the three models. Those from the MRF and the UKMO runs are for 0000 UTC, while those for the ECMWF runs are for 1200 UTC. Verifying analyses are for the corresponding times.

Aside from the daily perturbations produced by the mobile systems, the predominantly negative height anomalies until about 20 December can be seen in Fig. 2. These were reasonably well predicted, except by the ECMWF during the first week. The dramatic height rise at this time, signaling the change in regime, was well anticipated by all three models at 120-h range, although a day late in the MRF. Thereafter, weekly averaged analyzed height anomalies were positive except during the first week of January, as noted above. Forecast anomalies were likewise mainly positive in all models.

The very intense early-January trough was underestimated by all models, and was not anticipated at all at the time of its initial appearance. The shortcoming was most severe in the UKMO forecasts (which disdained extremes throughout the entire period) and least in the ECMWF forecasts, which included an extremely good one at the time of maximum trough development.

The end of January and the first few days of February saw a number of MRF and ECMWF forecasts of very low heights that failed to materialize. The most egregious errors occurred on 1 February, when the usually sedate UKMO forecast likewise threw caution to the winds. The 120-h forecast error in the Alaskan ridge (not shown) was also a maximum at this time. The unreliable behavior at 40°N, 65°W, however, had begun during the preceding week and so cannot be considered a consequence of failure to predict the blocking ridge. After the first few days of February, the errant models settled down to good behavior, especially so in the case of the MRF.

The coefficients of correlation at 40°N, 65°W between MRF-analyzed 500-mb height and forecasts produced by the three models are given in Table 1, along with additional measures. On the basis of correlation between forecast and analyzed height over the 84-day period, the ECMWF forecasts scored slightly higher than the others. During the 12 individual weeks, however, the 7-day correlations (appearing in Fig. 1) showed the MRF to be the best of the three models, by a small margin. The paradox is illuminated by noting the average magnitude of the weekly forecast bias and the average weekly rms deviation about this mean error. These are shown in Table 1. In the ECMWF forecasts, the mean error for the week tended to be smaller than that in the other models, but the scatter of daily errors about this mean was larger. In the MRF forecasts, contrariwise, the bias during the week was larger but the scatter of daily values was relatively small.

The UKMO was a model of conservatism, differing from its partners in failing to forecast extreme values. The rms deviation of the daily UKMO forecast heights from their mean value was 10.2 dam, while the deviations for the MRF and ECMWF were 13.6 and 14.6 dam, respectively, close to rms daily deviations in their verifying analyses of 14.6 and 14.3 dam, respectively.

The correlations for this location in Table 1 demonstrate for all three models a considerable skill in predicting day-to-day fluctuations due to mobile synoptic disturbances, since the correlations for a climatological mean forecast and for a 5-day persistence forecast were close to zero. Hence, there is reason to anticipate that predictions for the associated surface cyclones in the ERICA region would also be skillful out to a comparable range.

We note, incidentally, that the level of skill represented by the correlations over the 84-day period was limited by the occurrence of a small number of more-or-less consecutive days of horrendous forecasts. Note, for example, the large negative errors for the MRF verifying on 1–3 February. If the single forecast for 1 February is removed from the sample, the correlation for the UKMO model rises to 0.651, for the MRF to 0.678, and for the ECMWF to 0.701, while if the two-week period from 21 January to 3 February is excluded, the correlations rise to 0.723, 0.812, and 0.810, respectively.

TABLE 1. Comparison of predicted and analyzed 500-mb heights at selected points.

Model	84-day r[1]	MIW r[2]	AMIWME[3]	AIW rms[4]
		40°N, 65°W		
ECMWF	0.666	0.553	3.7	10.5
MRF	0.655	0.680	5.2	9.5
UKMO	0.631	0.673	4.4	9.7
		50°N, 130°W		
ECMWF	0.663	0.501	5.5	9.7
MRF	0.706	0.598	5.3	9.1
UKMO	0.632	0.493	8.3	10.2
		50°N, 20°W		
ECMWF	0.833	0.720	4.5	8.2
MRF	0.760	0.620	3.3	9.8
UKMO	0.734	0.584	5.3	9.4

[1] 84-day r is the linear correlation coefficient between analyzed and predicted 500-mb height over the 84-day period.

[2] MIW r is the mean correlation coefficient for the 12 individual weeks.

[3] AMIWME is the average magnitude of the mean error for each of the 12 individual weeks (dam).

[4] AIW rms is the average rms deviation from the weekly mean error, for each of the 12 individual weeks (dam).

To see whether these findings could be extended to other regions, a similar analysis of forecast and analyzed heights was carried out for points at 50°N, 130°W and at 50°N, 20°W. Results are shown also in Table 1. To judge from correlation coefficients, the UKMO model performed least well in both respects at both additional points, while differences were noted in the other models, each performing best nearest to home. There was a tendency for small weekly biases to accompany high overall correlations for the 84-day period, and for small rms deviations from the weekly mean error to accompany high correlations for individual weeks. Exceptions can be noted, however, and it is clear that the models performed differently from region to region, both in absolute terms and in comparison to each other. Again, the elimination of a small number of extremely poor

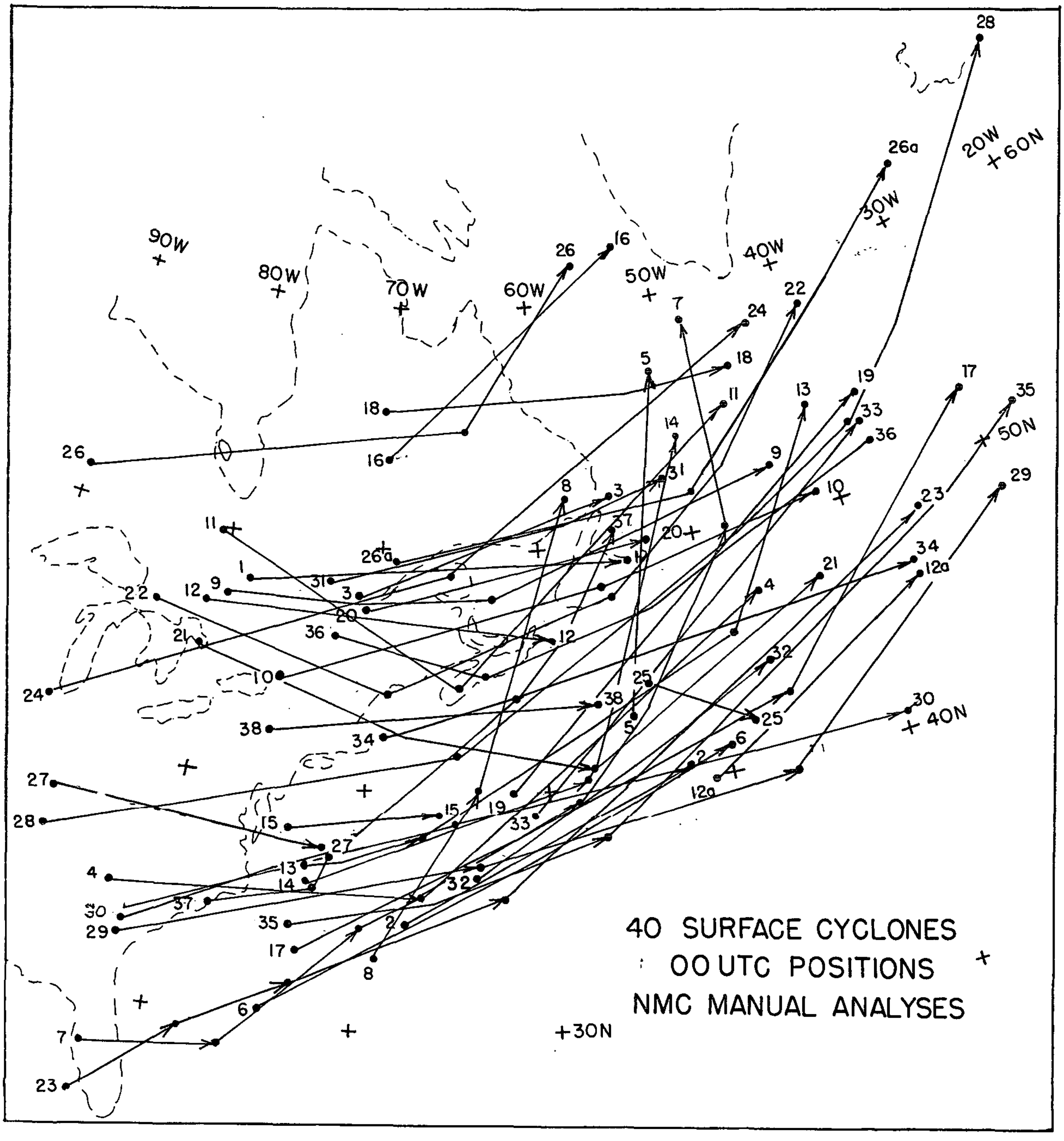

FIG. 3. Twenty-four-hour segments of the track of each Atlantic surface cyclone studied, with chronological number at the beginning and end. The dots show NMC manual-analysis positions at 0000 UTC.

forecasts (not shown) produced substantial rises in the correlation for the entire period. As at 40°N, 65°W, the forecast height values at the other two points were the most variable in the ECMWF and the least in the UKMO runs.

No single statement about model superiority can be made, but it appears from the correlations for individual weeks that all three provide skillful forecasts of the individual mobile systems at 500 mb, out to ranges of five days. This skill is apparently least for the point in the eastern Pacific region just off the west coast of North America, downstream from a vast region of sparse data, but even here it does not vanish entirely.

4. Surface cyclones

Positions and central pressures at 0000 and 1200 UTC were mapped for all persistent cyclones tracking through the ERICA region from December 1988 through February 1989. A persistent cyclone was one

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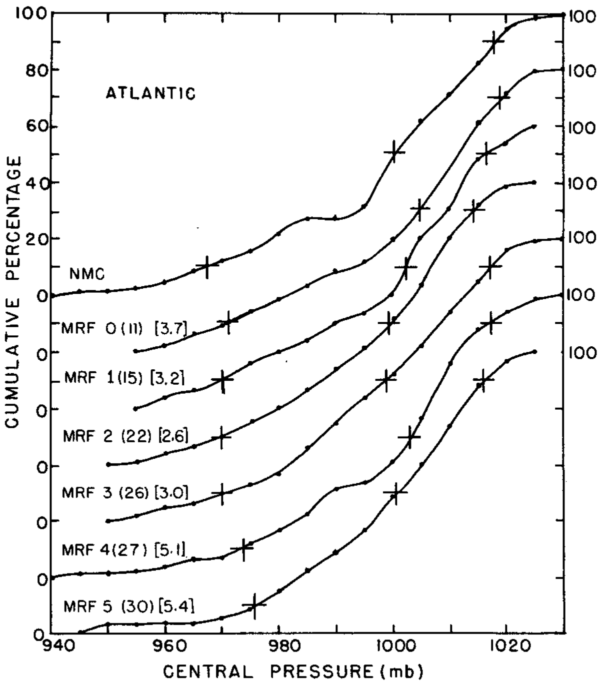

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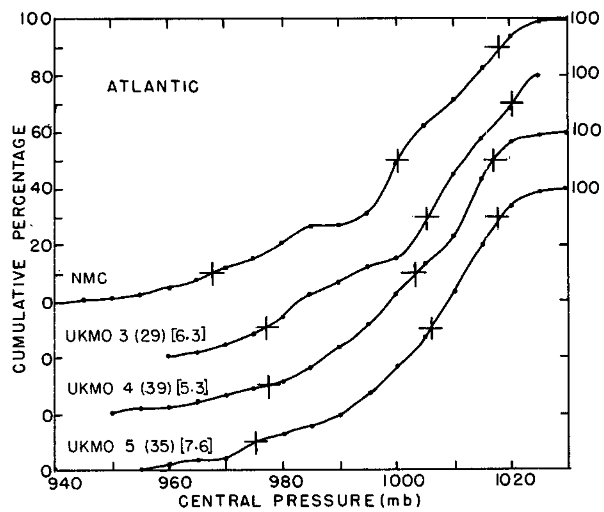

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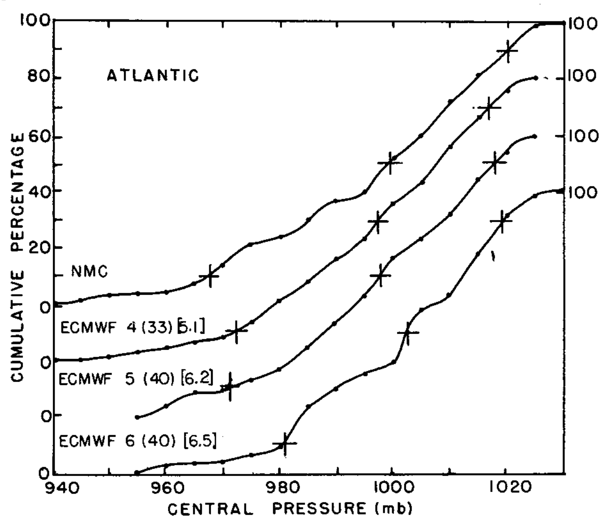


FIG. 4. Cumulative percent frequency of central pressures (mb) for the cyclones at the times examined, in the NMC manual analyses and in the forecasts at the number of days range indicated. The scale on the ordinate changes by 20% for each curve, as indicated. (The percentage of instances in which the available MRF prognostic map failed to show the center indicated in the NMC analysis is given in parenthesis. Values in brackets are the mean difference in the MRF forecast central value and the analyzed value, for all cyclones for which a match could be made.) Large crosses indicate the locations of the first, fifth, and ninth decile of each distribution. Forecasts for the MRF and UKMO models, with analyses at 0000 UTC, appear in (a) and (b), while the ECMWF forecasts, with analyses at 1200 UTC are shown in (c).

that could be identified on two or more consecutive NMC manual hemispheric analyses at 0000 UTC. The ERICA region was considered for this purpose to be the oceanic areas between 30°N and 55°N and between 50°W and the east coast of North America, although field observations were restricted to a much smaller area (Hadlock and Kreitzberg 1988). Some of the cyclones were tracked back as far as 90°W and some as far forward as 15°W. Decisions about which cyclones to track outside the ERICA region were made without regard to the forecasts.

There were 40 such individual cyclones. For each one, the corresponding position and central pressure was mapped for each MRF run in which it appeared. As sea truth, positions and central pressures were taken for each cyclone from the NMC manual analyses. Continuity of a surface cyclone was sometimes difficult to determine despite the 6-h interval between analyses, especially when the motion was rapid and multiple centers were shown. Subjective judgment was applied, with consideration given to the position shown in the MRF initial analysis, which was usually simpler. On rare occasion the analyzed central pressure was altered, when it appeared that a technical mistake had been made or when the analysis 6 h after a map devoid of data near the center, not available to the operational analyst, indicated a large error at the earlier time. Such decisions and alterations were made without reference to the forecasts. A few positions and central pressures were estimated by interpolation between the analyses 6 h earlier and later, when the desired map was missing.

A composite map of the tracks of the cyclones, in Fig. 3, shows a primary cluster over warm water from off the southeastern or Mid-Atlantic states, east-northeastward to about 800 km south of Newfoundland. There was a suggestion of a secondary maximum of tracks across the Gulf of St. Lawrence, with relatively few immediately south of Nova Scotia. Only cyclone 37 (ERICA IOP 8) ran northeastward along or close to the U.S. East Coast, consistent with a notable lack of snow at many points in this region.

Analyzed central pressures in the cyclones ranged from 1027 mb to 942 mb, with a median near 1000 mb, as shown in Fig. 4. The minimum value was analyzed for the ERICA IOP 4 storm ("14" in Fig. 3) noted earlier, near the time when a low-level research aircraft produced an even lower sea level value of 938 mb with strong wind. Cyclone speeds derived from 24-h displacements in the 0000 UTC NMC analyses (Fig. 5) had a median value of 32.5 kt (17 m s^{-1}) and ranged from 5 to 60 kt (3–31 m s^{-1}).

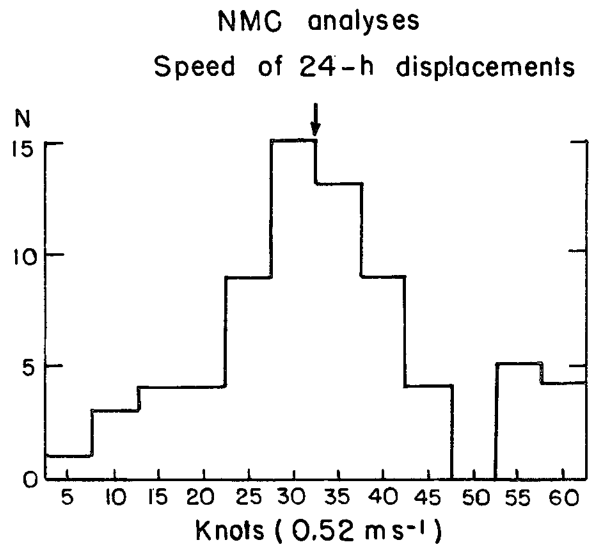


FIG. 5. Frequency of cyclone track speeds represented by 24-h displacements over the Atlantic, determined from 0000 UTC positions in the NMC analyses. The arrow indicates the median.

a. Predictions of central pressure

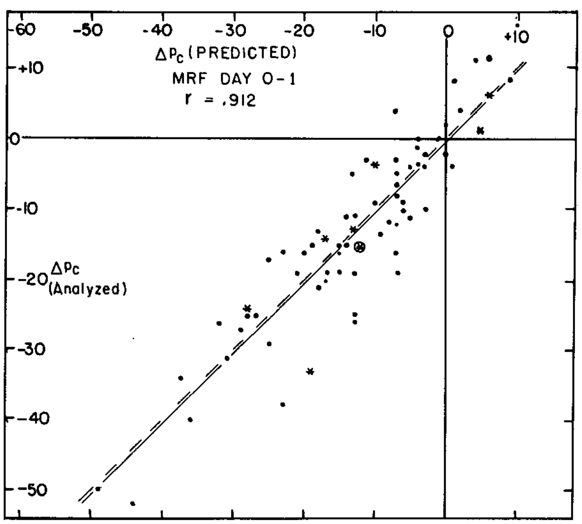
Generally, the positions and central pressures of the cyclones were read directly from the MRF prognostic charts received on AFOS. A few positions and pressures were estimated in cases where no center was shown but the shape of the isobar in a trough reached a minimum width and then bulged outward before reaching its cul de sac. In numerous other instances, the curvature and spacing of isobars indicated a maximum Laplacian of sea level pressure without the above characteristic. These were not included, but the estimated pressure at the location of the maximum Laplacian was used to determine change of pressure in a center appearing later or (sometimes) earlier. On other occasions, especially at the longer ranges, it was subjectively judged that no cyclone or Laplacian maximum existed in the forecast at a location that could reasonably be associated with the analyzed low center. The percentage of cases without forecast center is indicated in Fig. 4. Since the percentage of missing cyclones increased with range, we can infer that the forecasts at longer range displayed fewer low centers than did the verifying analyses, even discounting the numerous short-lived centers appearing in the verification. Except in the initial MRF analyses, the absence of an MRF low center occurred more than three times as frequently with the shallower half than with the deeper half of the systems, as shown in the NMC analyses. Thus, the missing centers tended to be weak ones, typically in the initial stage of the life history of the particular cyclone.

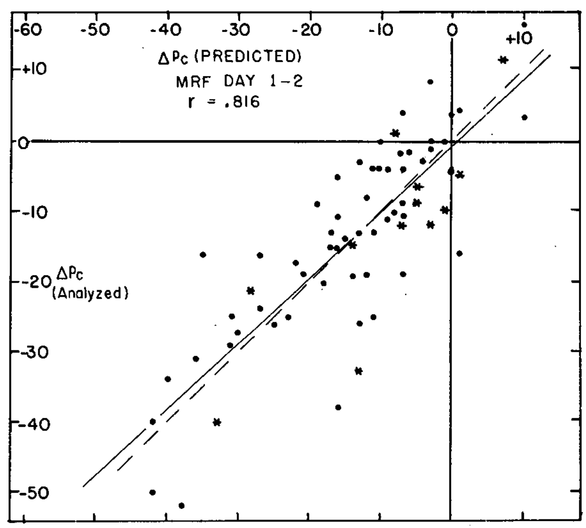
Cumulative percentages of central pressure for the cyclones appearing in the MRF runs at various ranges are shown in Fig. 4a. The distributions are closely similar to that for the NMC analyses, except for a median somewhat higher at some times, and with a lack of extremely deep centers on days 4 and 5, as shown by the drift of the first decile toward higher values. This result is somewhat misleading, however, because the missing centers in the forecast tended to be for shallower cyclones. Note in Fig. 4a that for all cases in which a match could be made, the MRF centers were shallower in the initial analysis and at all forecast ranges. The underestimation of intensity is consistent with the appearance of Laplacian maximum in the forecasts, corresponding to centers in the analyses.

These results are similar to those of many preceding investigations for the Atlantic region. Most recently, Smith and Mullen (1991) found that central pressures at 24-h and 48-h range in the earlier "aviation" (AVN) run of the same global spectral model were 2–3 mb higher on average when verified against the initial analyses of the nested-grid model (NGM). These analyses, in turn, to judge from evidence provided by Sanders and Auciello (1989) and Pauley et al. (1991), show central pressures less deep than those in manual analyses. Bramer and Pauley (1991) show how limited resolution of even the most detailed current models can produce these discrepancies.

Similar characteristics were found in the available UKMO and ECMWF forecasts, as can be seen in Figs. 4b and 4c. The 1200 UTC NMC manual analyses were used for verifying the latter, and evaluation procedures were the same as those applied to the MRF runs. The percentage of analyzed cyclones missing in the forecasts was somewhat greater for both of these models than for the MRF. The deepest centers in the analyses tended to be increasingly underestimated with increasing range in both models. The UKMO centers showed a slightly greater shortfall of depth overall than did centers from the other two models.

In forecasts from all three models, only a handful of persistent cyclones (no more than six 24-h periods





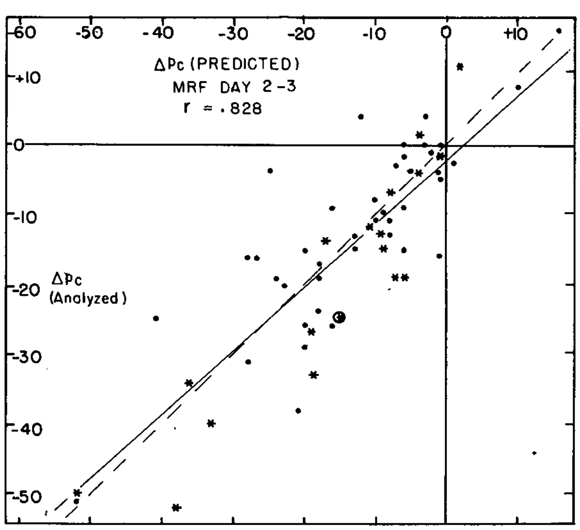


FIG. 6. Scattergrams of predicted *vs* analyzed central pressure change, for indicated ranges, from the MRF model and from the UKMO and ECMWF models as available. Dots indicate forecasts in which a low center was present at both the beginning and end of the 24-h period. Asterisks denote periods in which only a Laplacian maximum was present at one but not both of these times. Note that forecasts for the period from days 5–6 were available only for the ECMWF runs. Correlation coefficients are shown, with solid regression lines as well as dashed perfect-forecast lines.

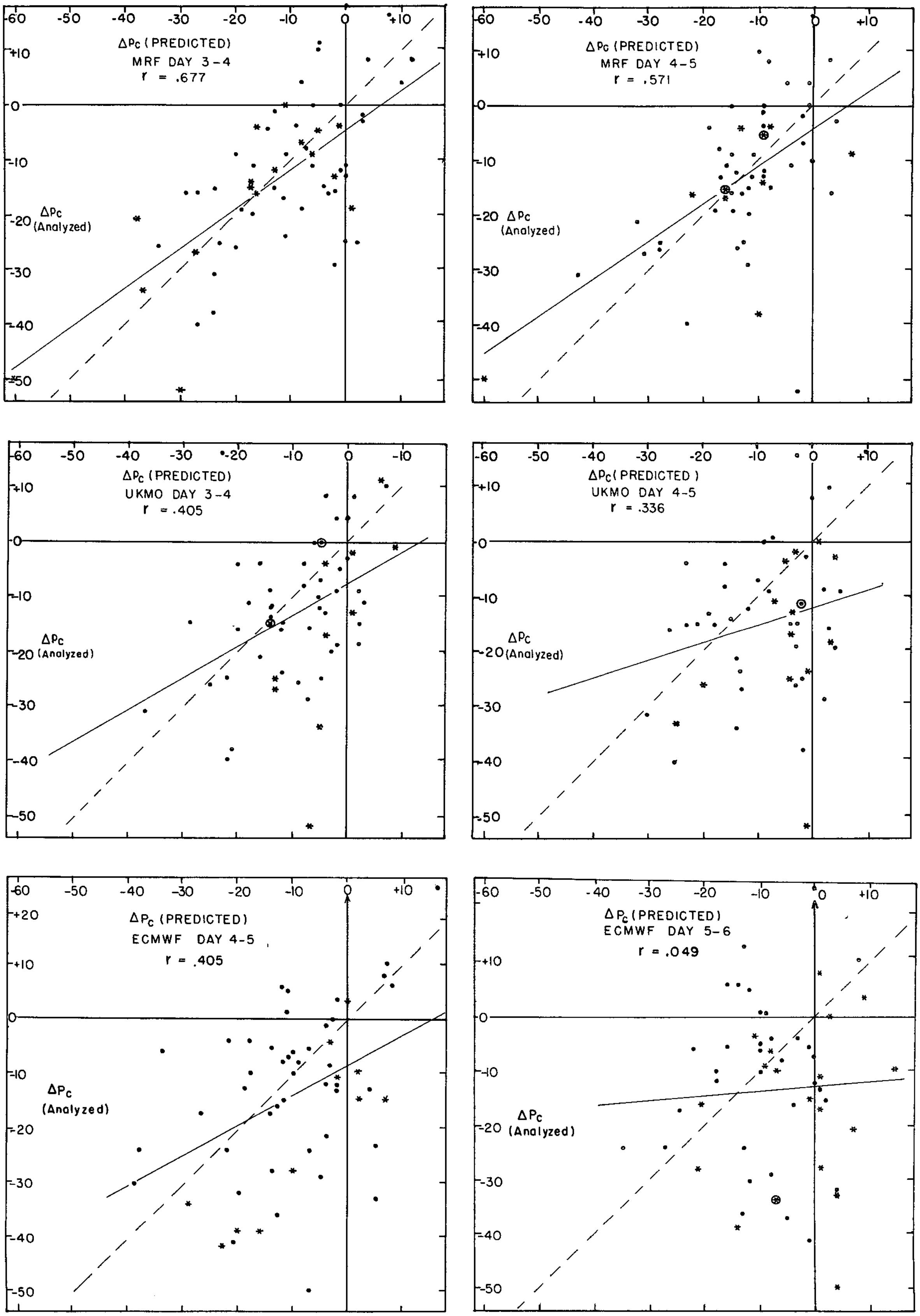


FIG. 6. (*Continued*)

for any model at any range) were present that could not be associated with some cyclone in the analyses. These "false alarms" were not considered.

b. Predictions of central pressure change

Since the western Atlantic region is a major cyclogenetic region, the models' ability to predict central pressure change is of interest even aside from the particular goals of ERICA. Thus, we compared the 24-h change in analyzed central pressure with the corresponding change in the model forecasts. To enlarge the sample (and to include many of the most interesting cases), we included forecasts in which a low center appeared only at the end (or sometimes the beginning) of the period, provided that the pressure could be estimated in a well-defined region of maximum Laplacian when the center was missing. This process was subjective but was undertaken without reference to the verifying analyses.

Comparison of analyzed and forecast changes for all three models is shown in Fig. 6. Correlation coefficients for the MRF are much higher than those given for the same area during the preceding cold season by Sanders and Auciello (1989) for the NGM and AVN runs. The forecast time resolution in the present study, however, is less stringent than in the earlier one, which dealt with 12-h changes. Moreover, the earlier study considered only cyclones that deepened explosively in either the analyses or the forecasts, while the present study required only persistence of the cyclone. Although comparisons are not strict, one cannot avoid feeling that the state of the art in prediction of marine cyclones has advanced substantially during the past 15 years from the poor state reported by Sanders and Gyakum (1980).

At the ranges for which comparisons can be made, the correlations between predicted and analyzed pressure change are notably lower for the ECMWF than for the MRF cyclones, and lower yet for the UKMO cyclones. The sample size is not large, however, and a few cases had a large impact in some instances. The near-zero value for the ECMWF lows from days 5–6, however, suggests that this model may at this range be near the limit of its ability in this respect.

The data in Fig. 6 suggest, and Table 2 confirms, that there was little bias in the MRF predictions of central pressure change. Predicted deepening fell short of analyzed deepening on average, but by less than 2 mb at any range. This is less than the 12-h shortfall for either NGM or AVN runs reported by Sanders and Auciello (1989) but their sample was biased toward strongly deepening storms, as noted. Table 2 shows, however, that a substantial underestimate of deepening occurred in the UKMO and ECMWF predictions.

c. Explosive cyclogenesis

Of this sample, 18 cyclones deepened explosively in the NMC analyses at 0000 UTC, on the basis of the one-bergeron criterion (Sanders and Gyakum 1980). (One bergeron represents a deepening of 14 mb in 24 h at 30°N, increasing to 23 mb in 24 h at 55°N.) Sixteen of these met the criterion during a single 24-h period, while two others did so in two consecutive periods. Thus, there were 20 explosion periods. ERICA IOPs occurred with six of these 18 storms.

The composite map (Fig. 7) shows that explosive deepening tended to concentrate over relatively warm water rather far to the south relative to the Sanders–Gyakum (1980) climatology and to the ERICA Atlas data as shown in the Field Operations Plan (Hadlock 1988). (As a result, in the ERICA flights a long ferry was often necessary to reach the storm area.)

The success of the MRF in prediction of this small sample of explosive periods can be assessed from the data in Table 3. The probability of detection (POD) for the right storm on the right day remained reasonably high out to maximum range, with about two-thirds of the events being anticipated in the first day of forecast range and nearly half beyond the third day ahead.

TABLE 2. Mean 24-h change in central pressure (mb).

			Range (days)					
Analysis	Model[1]		0–1	1–2	2–3	3–4	4–5	4–6
0000 UTC NMC			−12.7	−13.2	−13.1	−13.4	−13.1	
	MRF		−12.4	−13.3	−11.9	−11.5	−12.7	
		N	71	66	64	60	55	
0000 UTC NMC						−12.7	−14.8	
	UKMO					−8.4	−8.0	
		N				57	49	
1200 UTC NMC							−14.0	−13.4
	ECMWF						−9.8	−7.1
		N					57	54

[1] The average NMC-analyzed values for the MRF and UKMO comparisons differ because of the somewhat different group of cases included.

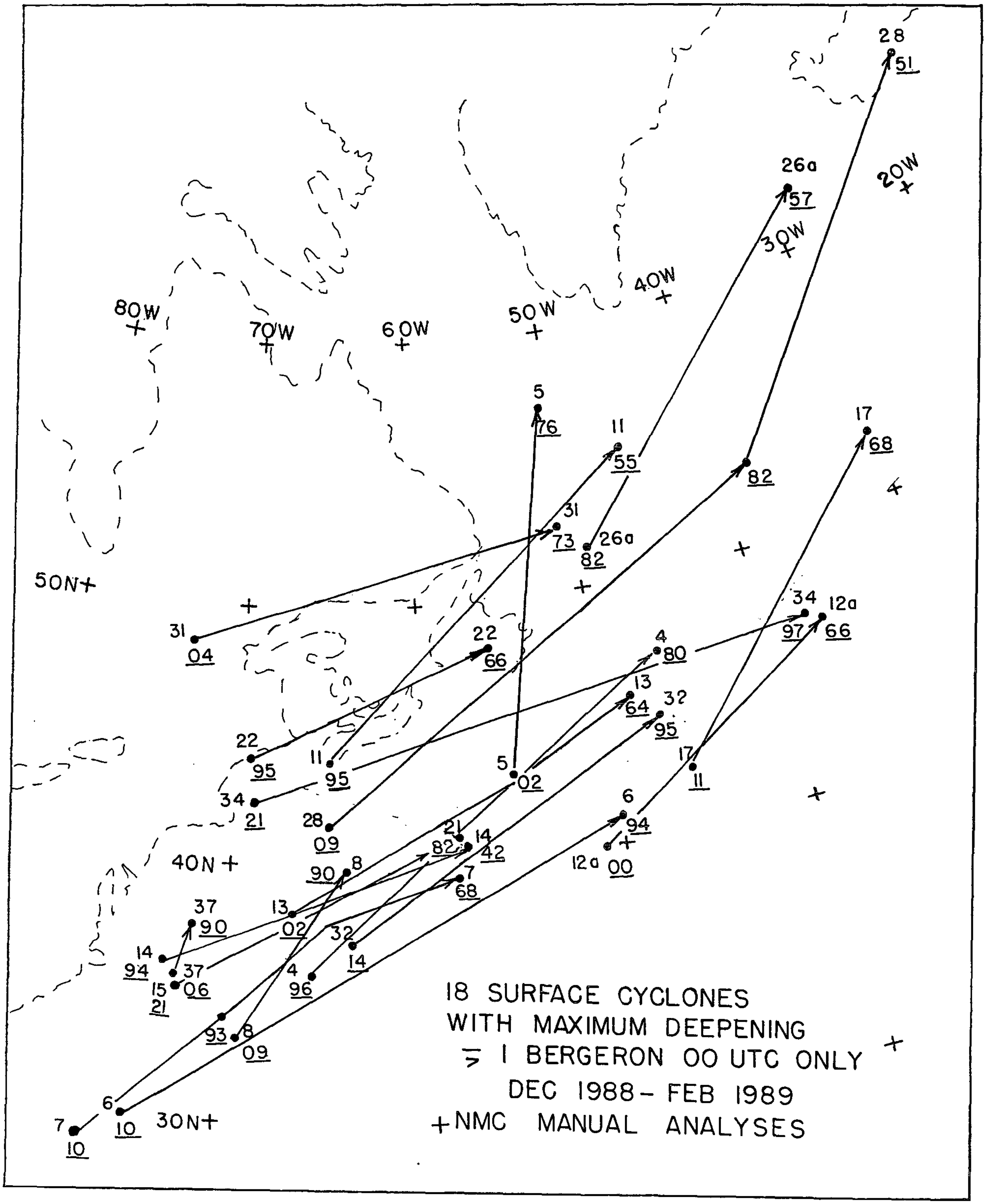


FIG. 7. Segments of tracks of surface cyclones shown in Fig. 3, for 24-h deepening of at least one bergeron, on the basis of NMC manually analyzed central pressures at 0000 UTC. The chronological case number is shown at the beginning and end of each segment, with the central pressure underlined (in millibars, with the hundreds and thousands digits omitted).

TABLE 3. Performance of the models in prediction of explosive cyclogenesis.

Range (days)	N^1	E^2	H^3	FA^4	POD[5]	FAR	CSI	CSI (NS)
				MRF				
0–1	71	20	14	4	.70	.22	.58	.15
1–2	70	20	12	6	.60	.33	.46	.16
2–3	70	20	11	5	.55	.31	.44	.15
3–4	71	20	9	6	.45	.40	.35	.14
4–5	70	20	9	3	.45	.25	.39	.12
				UKMO				
3–4	71	20	5	3	.25	.38	.22	.09
4–5	70	20	4	4	.20	.50	.17	.09
				ECMWF				
4–5	72	23	6	3	.26	.33	.23	.10
5–6	72	23	3	1	.13	.25	.12	.05

[1] N is the number of 24-h periods.
[2] E is the number of events: explosive deepenings in the NMC analyses.
[3] H is the number of events in which explosive deepening was predicted.
[4] FA is the number of instances of predicted explosive deepening that failed to occur in the analyses.
[5] POD is H/E; FAR is $FA/(H + FA)$; CSI is $[\mathrm{POD}^{-1} + (1 - \mathrm{FAR})^{-1} - 1]^{-1}$; CSI(NS) = $[N/(H + FA) + N/E]^{-1}$.

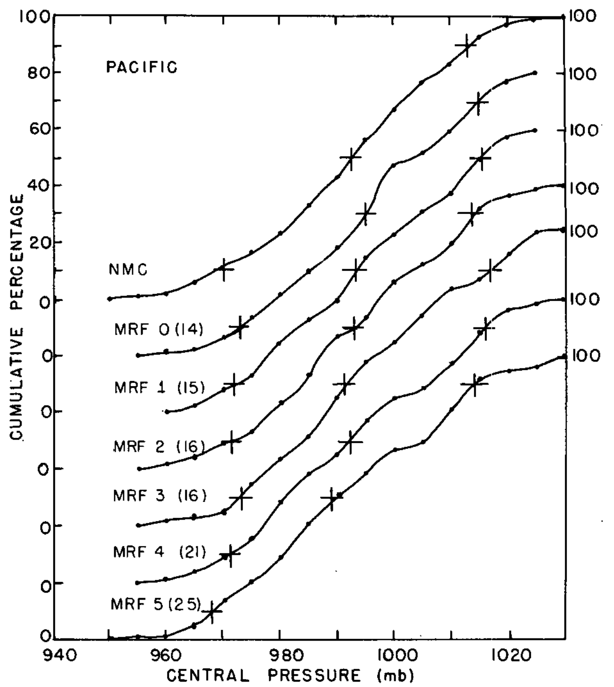


FIG. 8. Same as Fig. 4a, but for the eastern Pacific region.

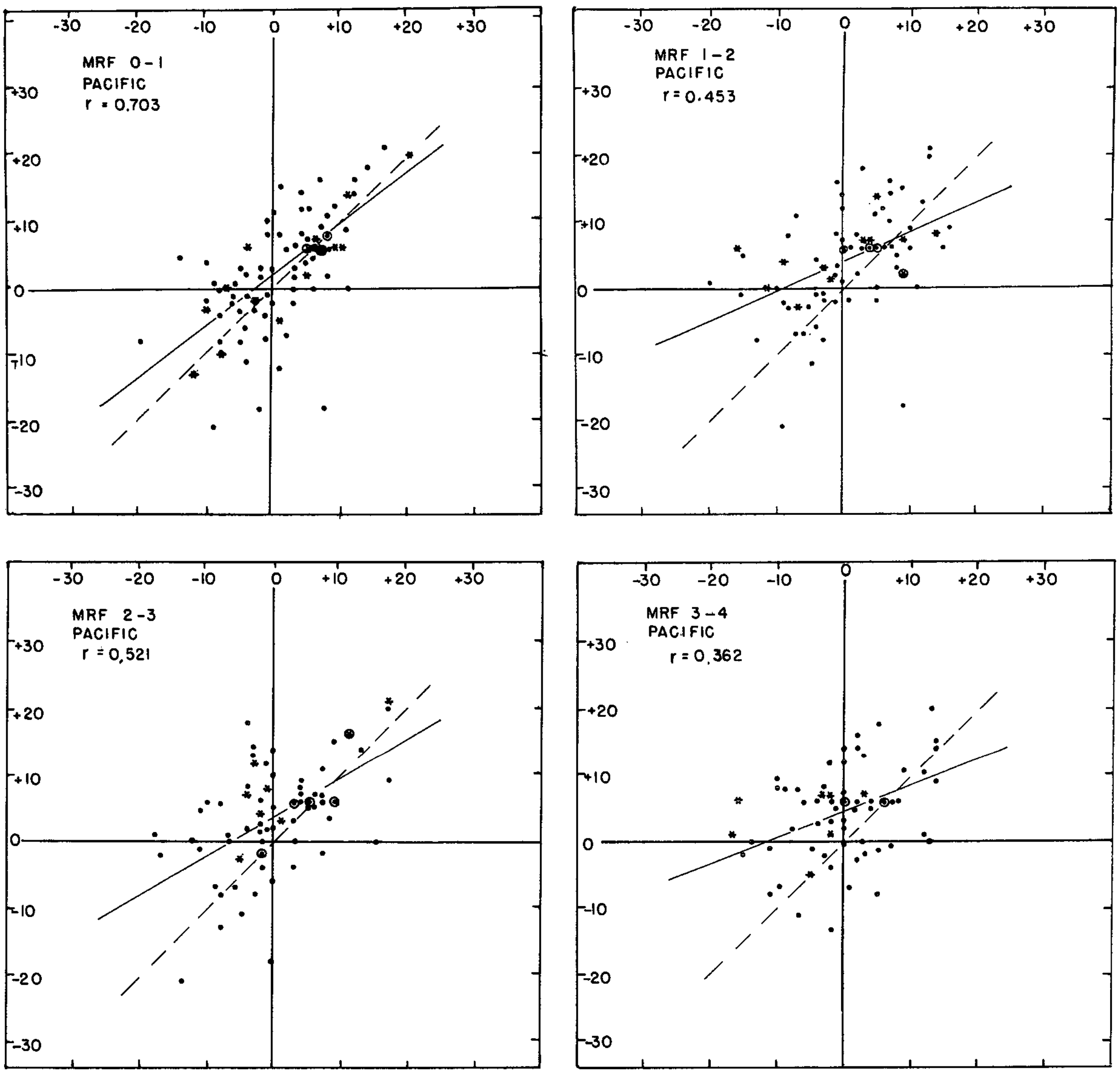
On the other side of the coin, false alarms were predicted in the MRF runs at one range or another for seven storms that failed to deepen explosively at any time in the NMC 0000 UTC analyses. In four additional storms explosive deepening was predicted on a day when it did not happen. It can be seen in Table 3 that the resulting false-alarm rate (FAR) did not vary systematically with forecast range.

The Critical Success Index (CSI) (Donaldson and Kraus 1975) was used to combine POD and FAR, yielding the values shown in Table 3. Sanders and Auciello (1989), for the NGM and AVN runs in a similar region during the preceding cold season, found CSI values of 0.63 for the NGM at day 0–1, slightly better than the present result. For day 1–2, however, the present results show a definite improvement over their values of 0.33 for the NGM and 0.37 for the AVN run. A decidedly larger POD is responsible despite a somewhat larger FAR.

Values for the UKMO forecasts appear also in Table 3 but only for the longer ranges. Relative to the MRF results there were fewer forecasts of explosive deepening, consistent with the smaller variability of forecast daily 500-mb heights, but a comparable number of false

TABLE 4. Mean magnitude of position error (PE, km) of cyclones with rms deviations in parenthesis and mean vector error (MVE, degrees per kilometer) Atlantic region, for model as indicated.

	Range (days)					
MRF	0	1	2	3	4	5
PE	154 (100)	254 (150)	314 (192)	468 (264)	643 (333)	767 (394)
MVE	178/56	203/75	250/96	243/157	244/211	250/204
N	100	94	86	82	82	77
UKMO				3	4	5
PE				558 (315)	696 (344)	813 (406)
MVE				297/70	022/158	273/87
N				79	70	74
ECMWF				4	5	6
PE				662 (399)	782 (446)	856 (532)
MVE				350/74	314/221	045/12
N				75	67	67



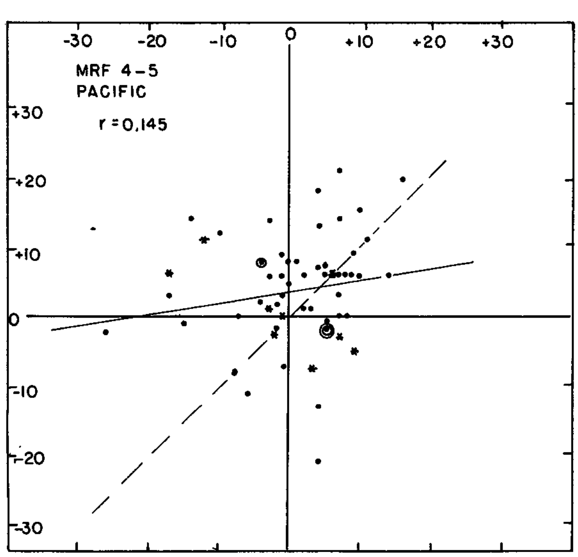


FIG. 9. Same as Fig. 6, but for the eastern Pacific region, and only for the MRF model.

alarms. Consequently, the CSI values are considerably lower.

The NMC analyses for 1200 UTC were used to evaluate the performance of the ECMWF model. These analyses showed explosive deepening in 19 storms, persisting for two days in four cases, so that there were 23 explosion periods. The 19 storms included the first five ERICA IOPs. As with the UKMO model, there were relatively few predictions of explosive deepening at the available longer ranges. (The false alarms for day 4–5 included one for a cyclone that failed to appear at all in the NMC analyses, but no special opprobrium was attached to this gaffe.) The CSI value for day 4–5 was higher than that for the UKMO forecasts but substantially lower than the MRF result. The extremely low value for day 5–6 is consistent with the low correlation coefficient for this model and time, as shown in Fig. 6.

The CSI score itself says little about skill. To determine skill, it is necessary to see what the scores would be for simple control forecasts and then to compare the actual CSI values with these. A forecast that explosive deepening would *never* occur would yield a CSI of 0.00. Against this control, all models showed skill at all ranges. A forecast that explosive deepening would *always* occur yields the result that CSI = E/N, the relative frequency of occurrence of the event. In the present case the data in Table 3 would yield 0.282 for 20 events in 71 instances, 0.286 for 20 events in 70 instances, and 0.319 for 23 events in 72 instances. On this basis, the MRF model showed skill at all ranges, but the other models showed no skill at any of the ranges examined. This result lacks inherent credibility.

Perhaps the most reasonable definition of skill would involve CSI scores obtained if the probability of explosive deepening were independent of whether it was predicted or not. Such a CSI score can be shown to be given by the formula for CSI(NS) in Table 3. Values depend on N, E, and H + FA (the total number of forecasts of explosive cyclogenesis) and are given in Table 3 for each model and range. On this basis, all three models have at least modest skill at all ranges.

The ability to show lack of skill by defining it relative to the CSI scores obtained by always saying "yes" seems unfair. Since such a forecast strategy, however foolish, is not unfair, this circumstance is a reflection on the CSI score itself. We find it fair to state that the models show skill in prediction of explosive deepening out to the limit of the ranges examined, and that the MRF runs appear to show the greatest skill for a given range. The sample size is small, however, and the results are precarious, if for no reason other than the arbitrariness of the one-bergeron threshold.

d. Predictions of position

Vector differences from the NMC analysis position of the cyclones to the forecast positions were determined for all cases in which a low center was present in the prediction. Cases in which a Laplacian maximum was used for the purpose of determining change of central pressure were excluded, because the relatively flat pressure field did not allow a determination of position with comparably small uncertainty. Results appear in Table 4. The mean magnitudes of position error for the MRF cyclones for the first two days are similar to those reported for the NGM in a similar region by Grumm and Siebers (1989a) for an overlapping period, by Mullen and Smith (1990), and by Smith and Mullen (1991) for the AVN forecasts as well. The present errors are perhaps somewhat greater for day 1 and smaller for day 2.

For ranges out to five days, the mean magnitude MRF position error grew at a remarkably linear rate of about 125 km day^{-1}, starting with approximately a 150-km difference from the NMC manual analysis position. This growth rate represents a speed of 1.4 m s^{-1}, less than 10% of the 17-m s^{-1} mean speed of the cyclones themselves. Where comparisons of mean magnitude of position error were possible, the ECMWF and UKMO model performed almost as well. Mean errors at the same range were slightly larger for the former model and larger yet for the latter.

There is some subjectivity in these errors, because of the difficulties with determining continuity of centers and the resulting question whether an analyzed cyclone was present at all on the forecast map. Position difference was a factor, of course, and a more liberal decision on identity would have reduced the percentage of analyzed lows not predicted, but at the certain cost of increasing position error. The differences between the models is not due to this subjectivity, however, because the percentage of missing lows in the UKMO and ECMWF forecasts, as well as the mean magnitude of position error, was larger.

The vector-mean position error for the MRF, shown in Table 4, was initially toward S, veering to WSW by

TABLE 5. As in Table 4, but for the Pacific region and for only the MRF model.

	Range (days)					
	0	1	2	3	4	5
PE	207 (165)	291 (195)	422 (322)	490 (323)	517 (325)	558 (369)
MVE	331/10	319/65	317/45	350/61	033/72	348/74
N	128	119	112	110	104	98

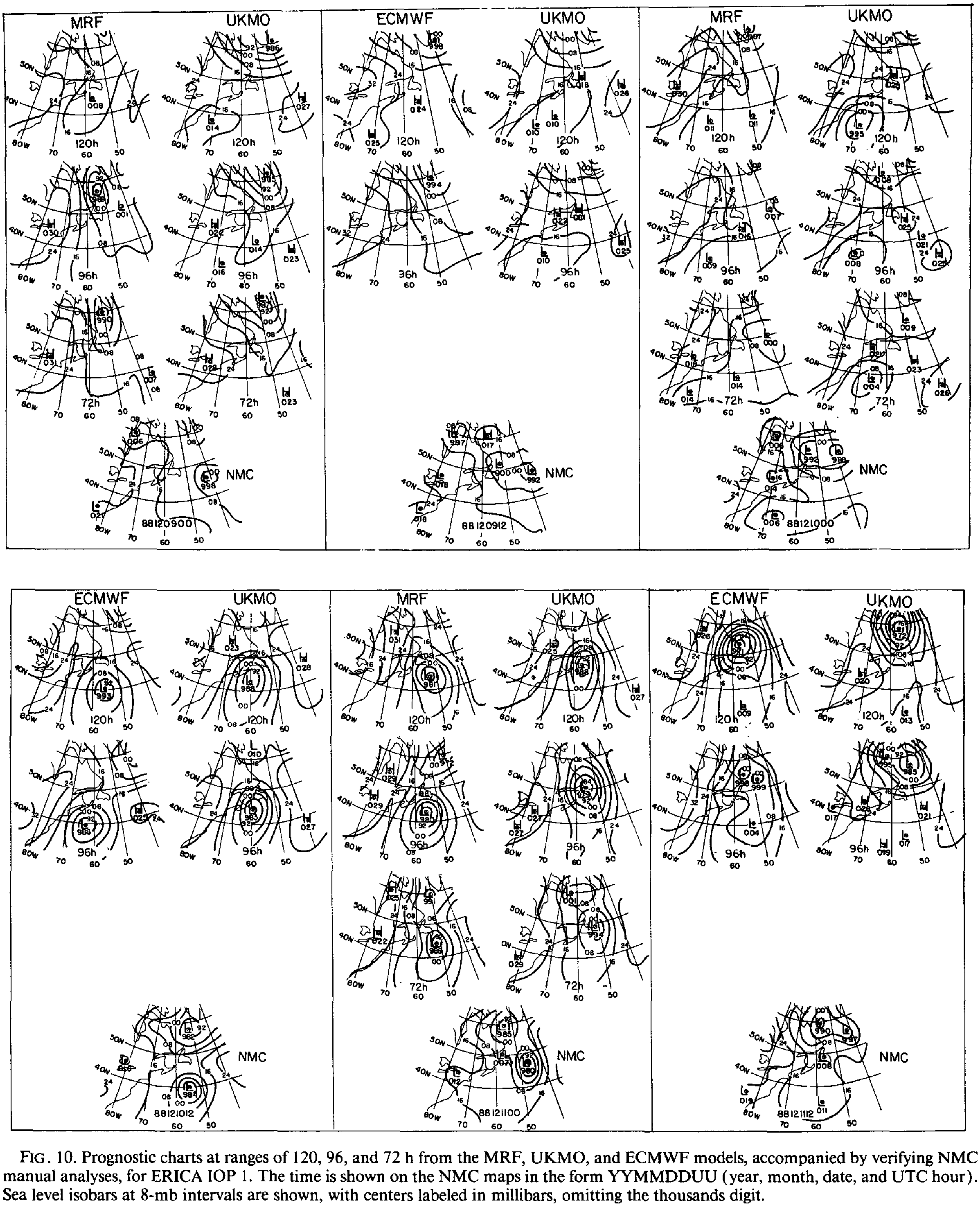


FIG. 10. Prognostic charts at ranges of 120, 96, and 72 h from the MRF, UKMO, and ECMWF models, accompanied by verifying NMC manual analyses, for ERICA IOP 1. The time is shown on the NMC maps in the form YYMMDDUU (year, month, date, and UTC hour). Sea level isobars at 8-mb intervals are shown, with centers labeled in millibars, omitting the thousands digit.

day 3. The other cited investigators found mean NGM errors for the first two days toward W or WNW. Had the model initial analysis (day 0) been used as sea truth, as in the cited studies, then the mean error in the present investigation would have been toward WSW and WNW on days 1 and 2. That is, the mean meridional

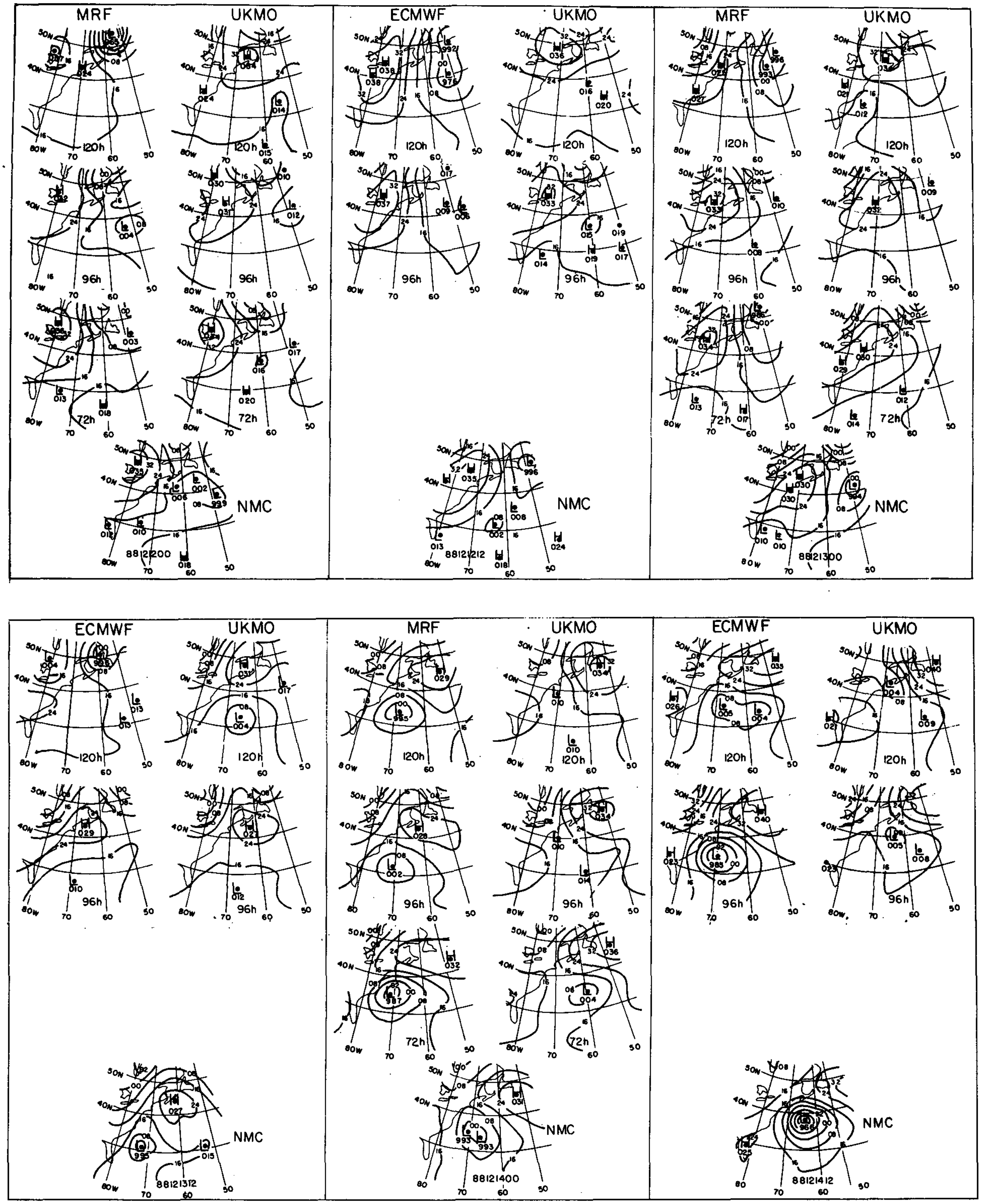


FIG. 11. Same as Fig. 10, but for ERICA IOP 2.

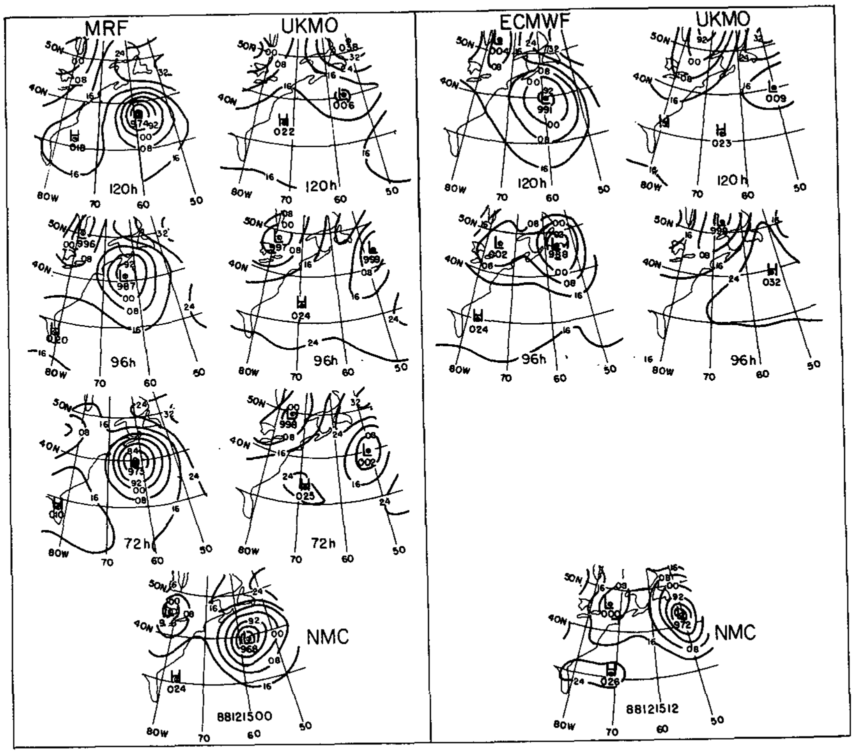


FIG. 11. (*Continued*)

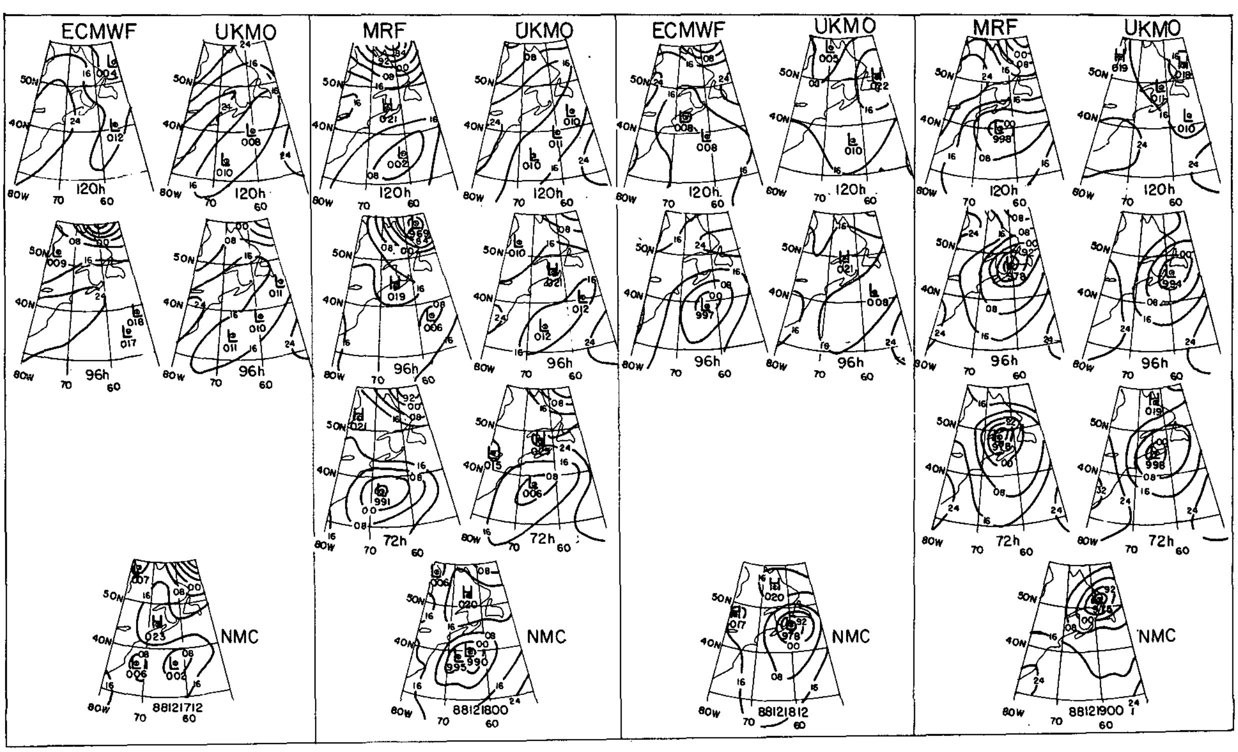


FIG. 12. Same as Fig. 10, but for ERICA IOP 3.

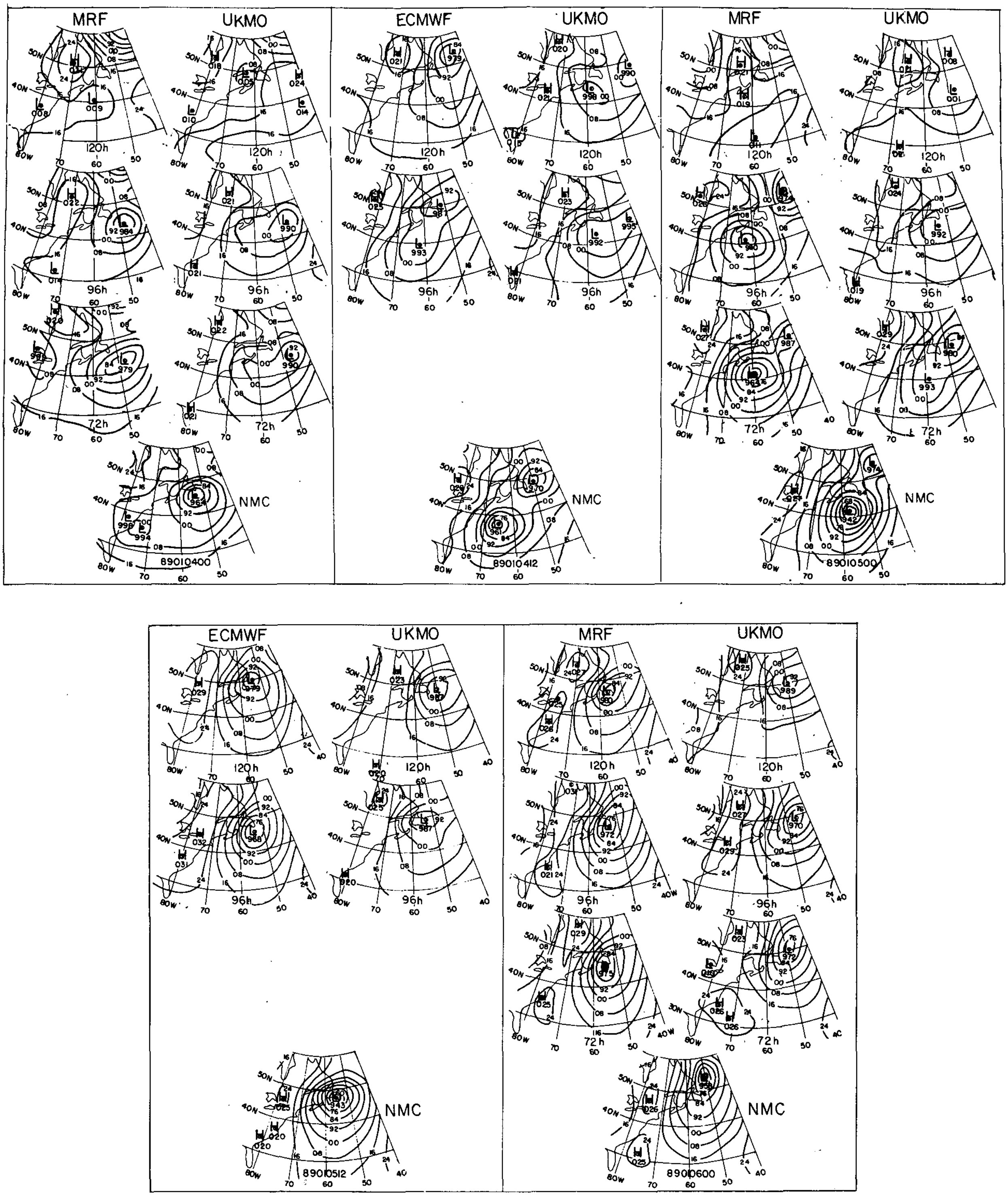


FIG. 13. Same as Fig. 10, but for ERICA IOP 4.

error in the MRF positions was toward S initially as well as in the forecasts, varying only slightly with range.

Zonal error, on the other hand, grew surprisingly steadily at the rate of about 43 km day^{-1}, or 0.5 m s^{-1}, indicating a small but persistent deficit in MRF-predicted eastward speed. However small, this systematic error was about 30% of the mean magnitude of position error. Mullen and Smith (1990) likewise found substantial mean NGM errors toward W in the Atlantic region. This result is surprising, since the responsible physical factors that come to mind (wave length, horizontal temperature gradient, effective static stability) should be accurately represented in both NMC models. Mean ECMWF and UKMO vector errors, in Table 4, were neither so large nor so consistent in direction. They were only slightly more than 10% of the mean magnitude of position error, and were predominantly northward and westward, with little regularity or trend.

e. MRF performance in the eastern Pacific region

To investigate the effects of varying data coverage and circulation regime on skill in prediction of surface cyclones, we considered all persistent cyclones in the eastern Pacific region, between a line from 51°N, 160°E to 18°N, 135°W (the limit of the available AFOS maps) and the west coast of North America. We required, as in the Atlantic, that the low be found on two or more consecutive NMC manual surface analyses for 0000 UTC.

There were 57 such cyclones from December 1988 through February 1989. The distribution of central pressures is shown in Fig. 8, where comparison with Fig. 4a shows that the Pacific cyclones lacked the number of outliers seen in the Atlantic sample, since the first and ninth decile fell at slightly higher and lower values, respectively. The median of the Pacific sample, moreover, was about 3 mb lower than its Atlantic counterpart. The track speeds of the Pacific cyclones were much slower than those in the Atlantic sample. The median speed was 12 kt (6 m s^{-1}) and only 6% moved faster than the Atlantic median speed (cf. Fig. 5).

The distribution of central pressures in the MRF runs also appears in Fig. 8. A complication was that in numerous instances a judgment had to be made whether the analyzed cyclone was missing altogether in the forecast map or whether it lay beyond the margin of the area available for examination. Where the latter option required an unreasonable position error, the cyclone was presumed to be missing. The decision was subjective, but was made without regard for the forecast. The percentage of missing centers, as seen in Fig. 8, was somewhat smaller than the Atlantic percentage. Recall that there the missing instances tended to be ones early in the life history of a cyclone, when it was poorly defined. The Pacific cyclones were older and better defined, on the average, and hence less likely to be absent on the prognostic maps.

As in the Atlantic case, the MRF initial analyses tended to show centers slightly less deep than the manual analyses. As forecast range increased, however, a difference in behavior became apparent: In the Pacific, the MRF forecasts tended to show centers increasingly deeper than the lows in the analyses. As will be seen, the model underestimated the average filling rate of the analyzed lows.

The correlation of MRF-predicted and analyzed 24-h deepening was determined as in the Atlantic case, with similar use made of maximum Laplacian to substitute for some of the missing forecast centers. Scatter diagrams appear in Fig. 9. Note that the Pacific correlations are substantially lower, the value for day 0–1 being only slightly larger than the Atlantic value for day 3–4. The difference increases with range, moreover, with the Pacific correlation approaching zero by day 4–5. These correlations are lower for a given range than the Atlantic correlations for either the UKMO or ECMWF models, although the Pacific performance of these latter was not evaluated. Examination of the scattergrams shows that on average, after the first day, the model predicted less than 1 mb of deepening or filling while the analyzed centers filled about 4 mb.

It was not possible to examine the MRF model performance in Pacific explosive cyclogenesis, because there was next to none during the three months examined. Specifically, one cyclone exceeded one bergeron in the analyses for 15–16 January. One forecast met this criterion, for day 4–5 verifying on a different day, 2–3 January.

Position errors were calculated as for the Atlantic sample, with results shown in Table 5. The difference between the NMC and MRF initial analyses is larger than in the Atlantic, but the growth of error is smaller, so that after day 3 the Pacific position error is smaller than the Atlantic one. Linear regression suggests for the Pacific a growth of about 71 km day^{-1}, starting from an initial discrepancy of about 235 km. This modest growth represents a speed of 0.8 m s^{-1}, a little more than 10% of the median track speed of the cyclones. Recall, however, that the larger growth rate in the Atlantic sample represented less than 10% of the median track speed, so that the Pacific position forecasts were relatively poorer.

The differences in central pressure and position error might be attributed to the characteristic difference in cyclone intensity and behavior between the two regions. The sudden intensification, rapid speed, and great depth of the major Atlantic systems, however, would seem to stress the model, suggesting a worse performance there, rather than a better one. It seems preferable to explain the difference on the basis of the uncertainty of the initial analyses over the central Pacific due to poorer data coverage, especially at the upper levels. Note in Table 1 that at the grid point just off the west coast of North America, the overall correlation of predicted and analyzed 500-mb height for the entire 84-day period was at least as high as for the point off the east coast. The correlations for individual weeks, however, were decidedly lower. A reasonable interpretation is that forecasts of the mobile waves were more sensitive to lack of good initial analysis than were forecasts of the slowly changing planetary scales. The re-

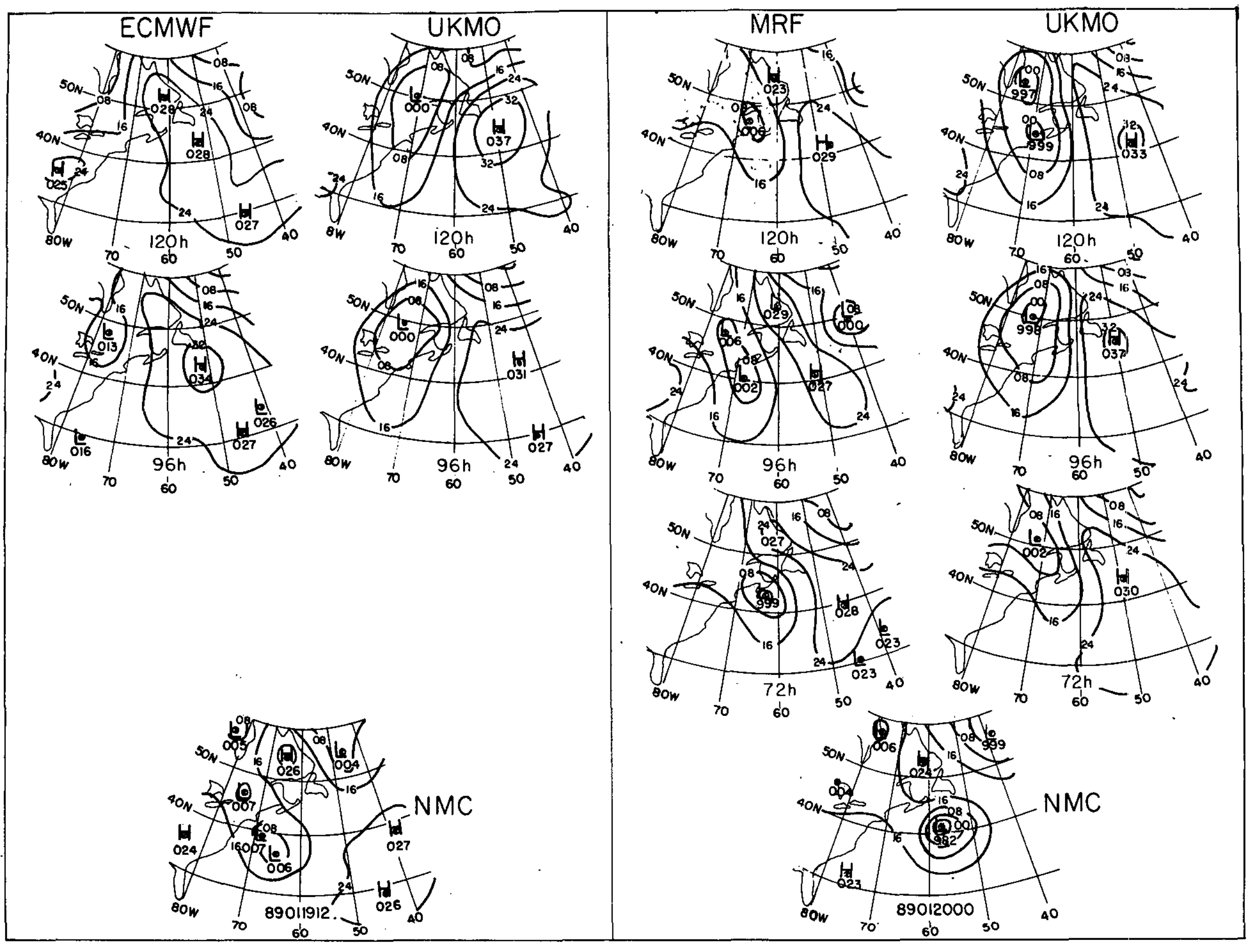


FIG. 14. Same as Fig. 10, but for ERICA IOP 5.

sulting inaccuracy is felt to have been responsible for the inferior prediction of the associated surface cyclones. The relatively large discrepancy in initial position of the surface cyclone reflects almost certainly the relative paucity of observations from ships, even at the relatively civil Pacific hour represented by 0000 UTC.

5. Some ERICA storms

There is particular interest in the storms occurring during the first five ERICA IOPs, since they all deepened explosively and will likely continue to be the focus of much ongoing research. These are cyclones 4, 7, 8, 14, and 21, whose tracks are shown in Figs. 3 and 7. The isobaric patterns for these systems are shown in Figs. 10–14 as they appeared in the NMC manual analyses and in the available model forecasts at ranges of 72, 96, and 120 h (days 3, 4, and 5). Initial analyses prepared by Sanders (1989), shortly after the end of the ERICA field phase but based on a more complete dataset than was available operationally, showed cyclones in similar positions. His central pressures ranged from 3 mb less deep (Fig. 11, 88121400) to 6 mb deeper (Fig. 11, 88121500, and Fig. 13, 89010500).[1]

The interest in these ranges was due to the long lead time required for major operational decisions. For example, the Field Operations Plan (Hadlock 1988) required declaration of Status Yellow as much as 65 h prior to the predicted onset of explosive deepening. This preliminary warning indicated at least a 50% chance of an operation. Assuming confirmation of portents, Status Orange was to be declared about 24 h later, at which time commitments for special field observations were made. Decisions after this time were numerous and important but largely in the nature of fine tuning. Given the lag between the time of initial analysis for a forecast run and digestion of its results, it is clear that Status Yellow relied mainly on the 72-h forecast. Some consistency between this and the 96-h forecast tended to add confidence to the decision,

[1] Time is shown as on the NMC maps in the form YYMMDDUU (year, month, day, and UTC hour only).

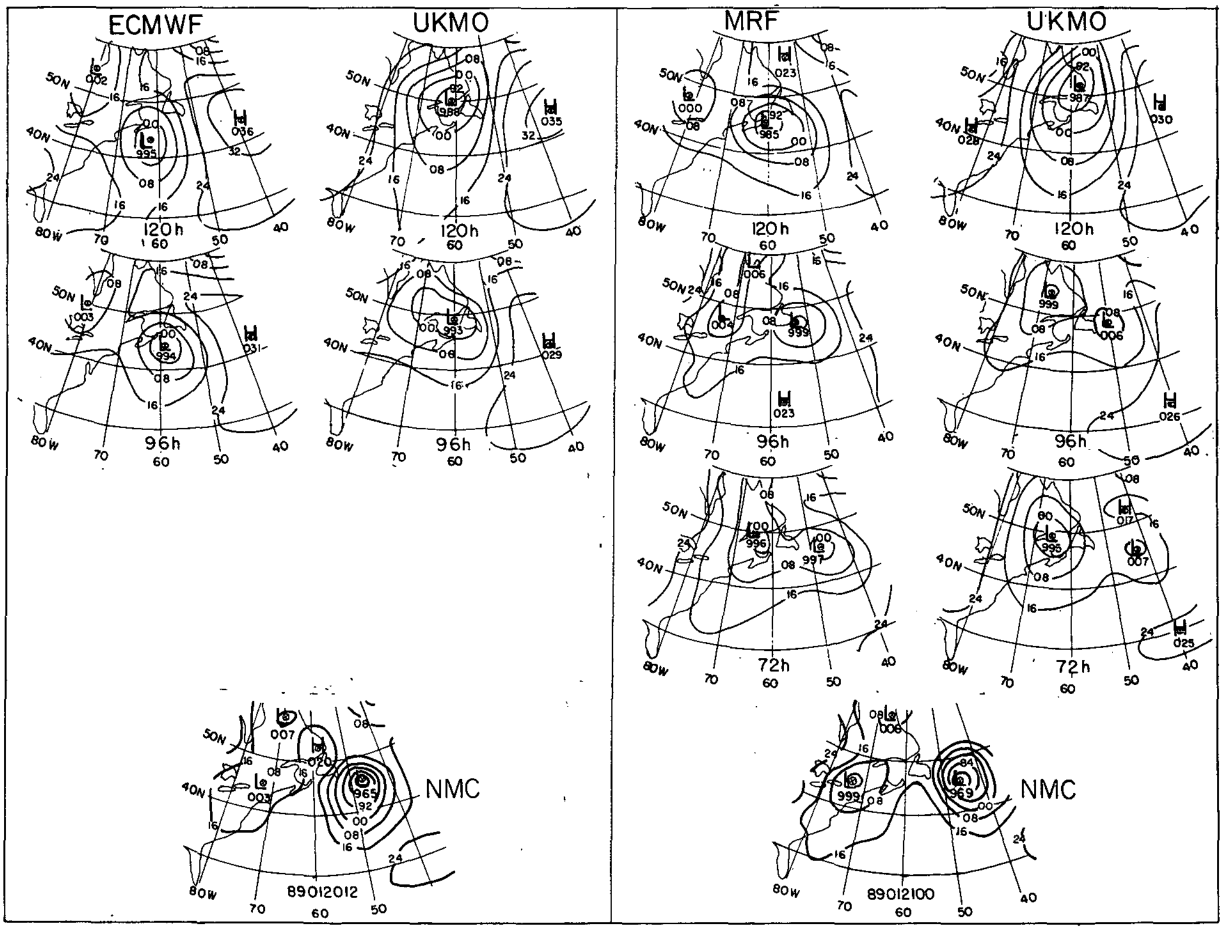


FIG. 14. (*Continued*)

and the 120-h forecast was a very useful basis for putting the forecasters on notice.

It is seen in Fig. 10 that for IOP 1 a storm of at least one bergeron was predicted by the MRF model at the range from 96 h to 120 h (day 4–5). (For example, the deepening from the 1009-mb center in the 96-h forecast verifying at 88121000 to the 981-mb center in the 120-h forecast verifying at 88121100 represents 1.5 bergerons at this latitude). The UKMO and ECMWF models concurred in the explosive prediction. Status Yellow was declared just prior to 0700 UTC 8 December, relying on the 72-h forecast verifying at 88121100. Status Orange followed less than 12 h later, the whole process being somewhat tardy, as the first aircraft reached the storm well after the onset of strong deepening. The ECMWF forecast might have encouraged an earlier start, had it been available at NMC sooner.

An ironical aspect of this case was that after the decision to go had been made, the shorter-range model guidance backed off, causing considerable forecaster anxiety. (Note the less-deep MRF and UKMO centers at 72 h than at 96 h.) In fact, the MRF initial analysis failed to show the occurrence of one bergeron, so had this analysis been taken as sea truth, the case would have been considered a false alarm. The NMC manual analyses, and the aircraft observations, however, confirmed that explosive deepening had indeed occurred.

Abundant warning was afforded by the MRF model for IOP 2 (Fig. 11), with strong deepening predicted to begin at 0000 UTC 13 December at a range from 96 to 120 h, and a major storm 48 h later. Status Yellow began at 0900 UTC 11 December, relying on forecasts verifying 88121400, and Status Orange followed 8 h later. The haste in getting an aircraft to the site may have been a reaction to the tardiness in IOP 1, and resulted in observations, however valuable, prior to the organization of a single definite center. (The NMC analysis for 88121312 is questionable.) The other models failed to match the performance of the MRF in this storm, with the UKMO model especially reluctant to follow up here (or hereafter, for that matter) its boisterous performance with IOP 1.

The immediately following storm, IOP 3, was not so spectacular (Fig. 12). Neither the analyses nor the MRF forecasts indicated more than a marginal one bergeron (except in shorter-range forecasts not shown).

Neither of the other models offered greater encouragement but, nevertheless, Status Yellow was declared at 1400 UTC on 15 December, with Orange following 8 h later. Evidently, the 72-h forecast verifying at 88121800 was sufficiently encouraging to warrant action, despite the 96-h forecast indicating a shallower low than the 120-h forecast.

In the case of IOP 4 (Fig. 13), there was no sign at 120 h, but 1.8 bergerons were predicted in the range from 72 h to 96 h, with even more intense deepening in subsequent forecasts. The dramatic 31-mb drop (and radical change in cyclone position) between the 120-h and 96-h forecasts verifying on 5 January had important operational ramifications. Earlier, the intent had been to explore a cyclone ("13" in Figs. 3 and 7) predicted to deepen explosively a day earlier along an almost identical track. The sudden indication of a more powerful storm a day later, however, led to abandonment of cyclone 13 in favor of 14, as Status Yellow, declared 1700 UTC 31 December in consideration of cyclone 13, was not followed by Status Orange until 48 h later. (In the event, cyclone 13 did deepen explosively and would have been a good storm for study, had logistical considerations permitted it. Perhaps the prospect and aftermath of New Year's Eve played some role.)

Operational considerations aside, the dramatic "fracture" between consecutive forecasts in this case deserves further study. The ECMWF model had a similar problem. Note in Fig. 14 the fracture between the 120-h and 96-h forecasts verifying at 89010412. The UKMO model was a day late and a pound short, forecasting explosive deepening after it had occurred and never approaching the depth predicted by the MRF model, itself considerably short of the depth known to have been reached.

The forecasts for IOP 5 (Fig. 14) showed something of a fracture in the reverse sense. That is, the 985-mb center in the 120-h forecast verifying at 89012100 was replaced by a center 14 mb weaker in the next run. The strongest deepening in the analyses, however, occurred a day earlier and was substantially more intense than the marginal explosive cyclogenesis in the 96- and 72-h forecasts verifying 89012000. Status Yellow was declared at 1900 UTC 16 January on the basis of these forecasts, however, and Status Orange began 25 h later, the closest to the ideal timing laid out in the Field Operations Plan. The other models performed similarly, forecasting explosive cyclogenesis but far short of the analyzed depth. They predicted a position much too far west, moreover, magnifying an error produced also by the MRF model.

6. Conclusions

In the central and western North Atlantic region, during the ERICA period December 1988–February 1989, explosive cyclogenesis tended to occur only when 500-mb heights were below the long-term average on planetary scale. With positive height anomalies in this region, cyclones moved rapidly eastward in strong zonal flow and intense deepening tended to occur to the north and east.

There is evidence that the MRF, ECMWF, and UKMO models showed skill at 500 mb out to at least five days' range, in prediction not only of the quasi-stationary planetary scales but also of the smaller mobile scales. The MRF forecasts were slightly superior in the latter aspect. The UKMO model systematically underestimated extreme values.

A large regime change in late December was successfully predicted by all models, but all failed in another large change at the end of January.

All three models displayed skill in prediction of the location and deepening rate of surface cyclones out to ranges of five days in the ERICA region, with verification taken from the NMC manual hemispheric analyses. Central pressures in the models were a few millibars too shallow on average, both in the initial analysis and in the forecasts. All models showed skill in distinguishing explosively deepening cyclones from others at all ranges. Skill decreased with range to small values at five days.

In the eastern Pacific region, a limited evaluation of only the MRF model performance showed a much lower skill in predicting 24-h deepening or filling, and a systematic tendency to underestimate the mean filling by a few millibars after the first day ahead. Explosive deepening almost never occurred during this 3-month period, in either the model or the real atmosphere, so skill could not be evaluated. Position forecasts were less skillful than in the ERICA region, except at ranges of four to five days. Even in this respect, the growth of position error with range represented a larger percentage of the much slower mean displacement speed of the Pacific cyclones.

The MRF cyclone forecasts were somewhat superior to those from the other models at all ranges for which comparison was possible, with respect to 24-h deepening or filling, identification as an explosive deepener, and center location. Forecasts from the ECMWF model were slightly better than those from the UKMO model.

Although exact comparisons could not be made, it seemed clear that the state of the art in prediction of marine cyclones has advanced substantially over the last 15 years. Use of the MRF runs in decision-making for the ERICA field project was highly successful, despite forecast failures at some ranges in a number of instances. No rapidly intensifying systems within reach of the project aircraft were missed, even though crucial decisions had to be made at ranges of 72 h and more prior to the start of major deepening. This forecast skill cannot be attributed to the special ERICA observations, since the special systems were deployed (except for some drifting buoys) only after the forecasts guiding the decisions had been made.

Conclusions concerning the relative performance of the three models cannot necessarily be extrapolated to other regions or to the present day. The models, for example, may be variously sensitive to the reduced quantity of data for initial analysis in the Pacific region. Further, all three models have evidently changed substantially since the winter of 1988/89. We urge, however, that this type of evaluation, centered on the behavior of mobile upper-level systems and surface cyclones, be continued as a supplement to the large-area anomaly-correlation determination that represents so strongly the slow-moving planetary scales.

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