Variability in Successive Operational Model Forecasts of Maritime Cyclogenesis

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ABSTRACT

The level of variability present in operational model simulations of marine cyclogenesis was examined. Successive forecasts valid for the same 12-h time period of analyzed maximum cyclone central pressure fall from the National Meteorological Center (NMC) nested grid model (NGM) and the Canadian Meteorological Centre (CMC) regional finite element model (RFE) were examined for one cold season (November 1988–March 1989). All cyclones with an analyzed 12-h maximum central pressure fall occurring within the Western Atlantic region were included in the study, comprising a total of 52 sets of 0–12-, 12–24-, 24–36-, and 36–48-h forecasts.

Analyzed cyclone development spanned a wide range of intensities, from no development (one case) to extraordinarily rapid development (greater than 24 mb in 12 h, 14 cases). The primary storm track was located offshore, resulting in reduced precipitation along the coastal regions. Both models tended to under-forecast cyclone development, and under-represent the clustering of cyclone activity within a narrow band offshore. This tendency became progressively stronger in the NGM with forecast range, while the behavior of the RFE was complicated by an apparent short-range (0–12-h) spin-up problem.

The degree of variability in a sequence of forecasts was not well related to the overall prediction error for either model, belying the view that consistency in successive model forecasts indicates reliability. Each model exhibited forecast sets of low variance with high error (consistently poor forecasts of development) and sets of high variance with low error (inconsistent, but within range of the analyzed development). The models performed more similarly with regard to their mean error characteristics for a given set of forecasts than in terms of the dispersion of that error within the forecast sequences.

1. Introduction

Ample evidence exists to demonstrate that the more severe or "explosive" occurrences of maritime cyclogenesis represent a serious hazard in the offshore environment. Notable cyclones include: 9–12 September 1978, in which the *Queen Elizabeth II* ocean liner was damaged and the fishing vessel "Captain Cosmo" sank; 13–14 August 1979, which disrupted the Fastnet race at the cost of 15 lives and 5 sailing vessels; 12–15 February 1982, in which both the drill rig *Ocean Ranger* and the Soviet container ship *Mekhanik Tarasov* went down (claiming a total of 117 lives); and recently, 13–15 December 1988, in which two fisherman drowned and the 14 000 ton drill rig *Rowan Gorilla* capsized while under tow 1000 km southeast of Halifax. This last storm is of particular interest since enhanced observations of its structure are available through data collected in the Experiment on Rapidly Intensifying Cyclones over the Atlantic (ERICA; see Hadlock and Kreitzberg 1988) during Intensive Observation Period (IOP) number two.

Considerable research effort has been exerted in an attempt to understand the physical basis of these phenomena. Simultaneously, operational numerical weather prediction models have improved their forecasts of explosive marine cyclogenesis in recent years to the extent that Sanders (1987) suggests that all of the physical ingredients crucial to this cyclogenesis, and evidently unique to the maritime environment (Roebber 1984, 1989), exist in the models. However, despite these recent successes, as will be shown in section 3, considerable variability in predictions of cyclogenesis often exists for successive forecasts validating for the same 12-h period of analyzed maximum cyclone central pressure fall (hereafter referred to as lagged forecast ensembles, after Hoffman and Kalnay 1983). The work reported in this paper represents an attempt to document the extent of this forecast ensemble variability for marine cyclogenesis in the Western Atlantic for the 1988–89 cold season. Sections 2 and 3 describe the methodology followed and the results obtained.

2. Methodology

The extent of Western Atlantic cyclogenesis forecast variability was investigated in the National Meteorological Center (NMC) and Canadian Meteorological Centre (CMC) operational dynamical models (the

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nested grid model or NGM and the regional finite element or RFE, respectively) for one winter season (November 1988–March 1989). Descriptions of these models are given by Hoke et al. (1989) and Benoit et al. (1989). All cyclones with an analyzed 12-h maximum central pressure fall (minimum central pressure rise) occurring within the region offshore of eastern North America and west of the model facsimile display boundaries (shown as the solid line in Fig. 3), were included in the study. Ground truth was based upon the six hourly manual NMC final surface analysis. A cyclone in the *analysis* was defined as a relative minimum in sea-level pressure, enclosed by at least one isobar (analyzed at 4-mb intervals), which appeared on at least three successive analysis charts. The 12-h time period of cyclone maximum central pressure fall was chosen as the nominal period of interest, based on the assertion that a model's utility may best be defined by its ability to forecast significant change in a cyclone's intensity. The model cyclones were identified based upon subjective comparison with the analyzed fields. When an offshore cyclonic development was not fully captured, it was sometimes necessary to identify a surface trough rather than an enclosed low pressure area as the corresponding model cyclone. For such cases, a central pressure value was estimated within the trough. However, for the majority of cases, and particularly at shorter forecast range and for stronger developments, there was a close correspondence between analyzed and modeled surface cyclonic pressure fields.

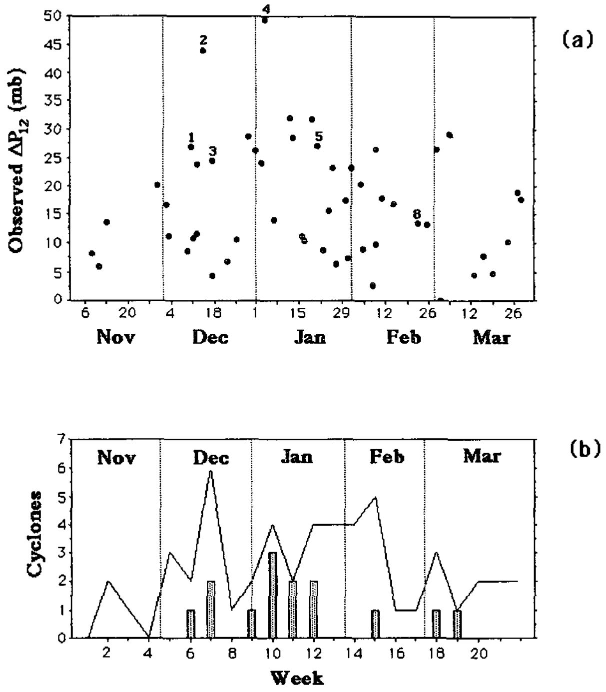


FIG. 1. (a) Distribution of Western Atlantic cyclone maximum analyzed 12-h central pressure fall for the 1988–89 cold season. Labelled points indicate ERICA IOP number. (b) Number of cyclones per week for the 1988–89 cold season. Bars indicate the number of cylones with 12-h central pressure falls greater than 24 mb/12 h.

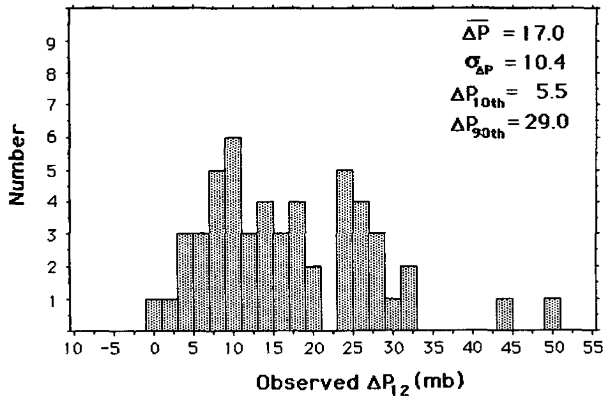


FIG. 2. Frequency plot of analyzed 12-h central pressure fall for the Western Atlantic 1988–89 cold season cyclones. Summary central pressure fall statistics include: the mean (ΔP), standard deviation ($\sigma_{\Delta P}$), and the 10th (ΔP_{10th}) and 90th percentile (ΔP_{90th}) central pressure falls.

The analyzed and modeled 12-h pressure change data were then normalized to an equivalent pressure change at 60°N (hereafter referred to as ΔP_{12}; see Sanders and Gyakum 1980) and compared for each ensemble of forecasts (52 ensembles) representing forecast ranges of 0–12, 12–24, 24–36, and 36–48 h. Analyzed/modeled intensification rates and positions were tabulated for each forecast of each ensemble. Variability was assessed by computing the standard deviation of the model 12-h pressure change errors for each ensemble. The results of this analysis are presented in section 3.

3. Results

a. *Analysis vs. climatology*

Figure 1 shows the distribution of the analyzed central pressure fall and cyclone frequency as a function of date for the entire sample period (November 1988–March 1989). A frequency plot of the analyzed maximum 12-h cyclone central pressure fall is shown in Fig. 2, along with basic distribution statistics. Cyclogenesis spanned a wide range of intensities, from no development (1 case) to extraordinarily rapid development (greater than 24 mb in 12 h, 14 cases). Offshore cyclogenesis was highly active beginning in mid-December, continuing after a short pause Christmas week through mid-February. Extraordinarily intense cyclogenesis occurred in mid-December and particularly, through the first three weeks of January, resulting in a total of 14 storms for the season that developed at a rate of at least 2 mb/h for 12 h. In the peak months of December–February, 12 of these particularly rapid developments occurred. Figure 3 shows the location of

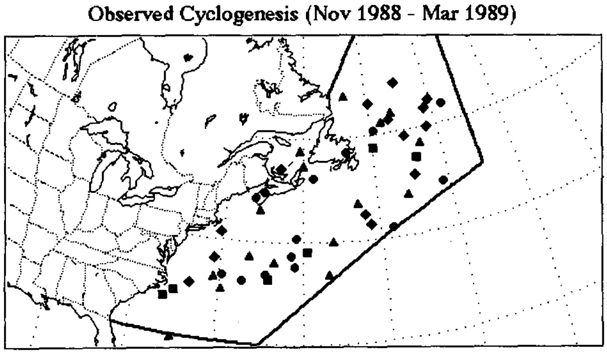


FIG. 3. Maximum deepening positions of Western Atlantic 1988–89 cold season cyclones. The bold line indicates the study boundary and the symbols correspond to 12-h cyclone central pressure falls of less than 6 mb (■), 6–12 mb (▲), 12–24 mb (♦), and greater or equal to 24 mb (●).

the mid-point of the cyclone maximum 12-h deepening period. It is evident that Western Atlantic cyclone activity was occurring well-offshore, which resulted in anomalously low precipitation along the eastern seaboard for the period December 1988 through February 1989 (see Climate and Diagnostics Bulletin, NOAA, 88-12 through 89-2).

It is of interest to compare the 1988–89 cold season activity with climatology, in order to gain some perspective on the nature of the past season. Hadlock and Kreitzberg (1988), using a less stringent development criteria (10 mb per 6 h), found 104 cyclones in the Western Atlantic in the 22-year cold season period (1 December 1965–28 February 1987), corresponding to slightly less than five storms per three months. Roebber (1984) found substantial differences in the positions of explosive cyclogenesis, based on a 24-h development criterion, for two 3-year periods in the Western Atlantic (1976–79 and 1979–82). In order to examine the dependence of the intensity of cyclogenesis on cyclone location, the data from Roebber (1984) were stratified as a function of cyclone maximum deepening rate and maximum deepening position. The results of this re-analysis are presented in Table 1. The data indicate that cyclogenesis was more intense during the 3-year period in which the cyclone track was shifted farther offshore. Hayden (1981) demonstrated, using cyclone frequency data for the period 1885–1978, that the mean storm track runs along a line from Cape Hatteras to Halifax, but that considerable variability in cyclone frequency exists along the western boundary of the Gulf Stream. This suggests that an offshore storm track is an anomalous, but not infrequent, occurrence. Resio and Hayden (1975) showed that the seaward displacement of the mean storm track is associated with increased severity of Atlantic storms. Colucci's (1976) cyclone climatology, based on ten years of winter data, also demonstrates the existence of two discrete cyclone tracks: a primary track along the continental margin, and a secondary track along the western boundary of the Gulf Stream, the latter of which was characterized by more rapid cyclogenesis.

b. Analysis vs. forecast

Figures 4 and 5 show the corresponding model (NGM, RFE) cyclone deepening distributions for each of the forecast ranges. Summary statistics for model performance at each of the forecast ranges, in terms of the distribution of model errors in deepening rates, are shown for the 1988–89 cold season in Table 2. These results demonstrate a tendency in both models to under-forecast cyclone development. In the NGM, this tendency is demonstrated by a monotonically decreasing mean 12-h cyclone central pressure fall (or alternatively, an increasingly negative mean forecast pressure change error) with forecast range. This bias is also represented by the increasingly negative skewness values, which show an increase from 0.8 to 2.5 standard deviations below zero across the range of 12 to 48 h.

Sanders (1987) found that the NGM C-grid forecasts for the cold season of 1986–87 predicted a mean 12–24-h deepening of 9.9 mb, compared to the analyzed value of 11.0 mb. Sanders and Auciello (1989) demonstrated that for the cold season of 1987–88, the NGM predicted a mean 12–24-h deepening of 9.4—2 mb weaker than the analysis. In contrast, for the 1988–89 cold season, the NGM forecast a mean 12–24-h deepening of 10.8 mb, compared to the mean analyzed deepening of 17.0 mb. Although the case selection criteria employed in this study is somewhat different than that of the above papers (which examined NGM forecasts 12–24 h after initialization and validated periods of analyzed explosive cyclogenesis based upon a 24-h criterion), the apparent degradation in performance of the NGM in forecasting Western Atlantic cyclogenesis for the 1988–89 cold season is conspicuous. Sanders (1987) showed that the NGM performance degraded substantially in his sample outside of the high resolution C-grid region. However, all of the events in the present study are contained within the expanded C-grid region (Hoke et al. 1989), so this effect is not likely to be a significant factor here. Reference to Fig. 6a of Sanders (1987), Figs. 1 and 3a of Sanders and

TABLE 1. The number of Western Atlantic 24-h explosive cyclones ($B \geq 1.0$) for six cold seasons (based on data from Roebber, 1984). (ΔP is in mb, ϕ in degrees latitude)

	Number of explosive cyclones $\left(B = \dfrac{\Delta P \sin 60°}{24 \sin\phi}\right)$			
Period	$1.0 \leq B < 1.5$	$1.5 \leq B < 2.0$	$B \geq 2.0$	Total
1976–79	89	20	15	124
1979–82	83	21	6	110
Total	172	41	21	234

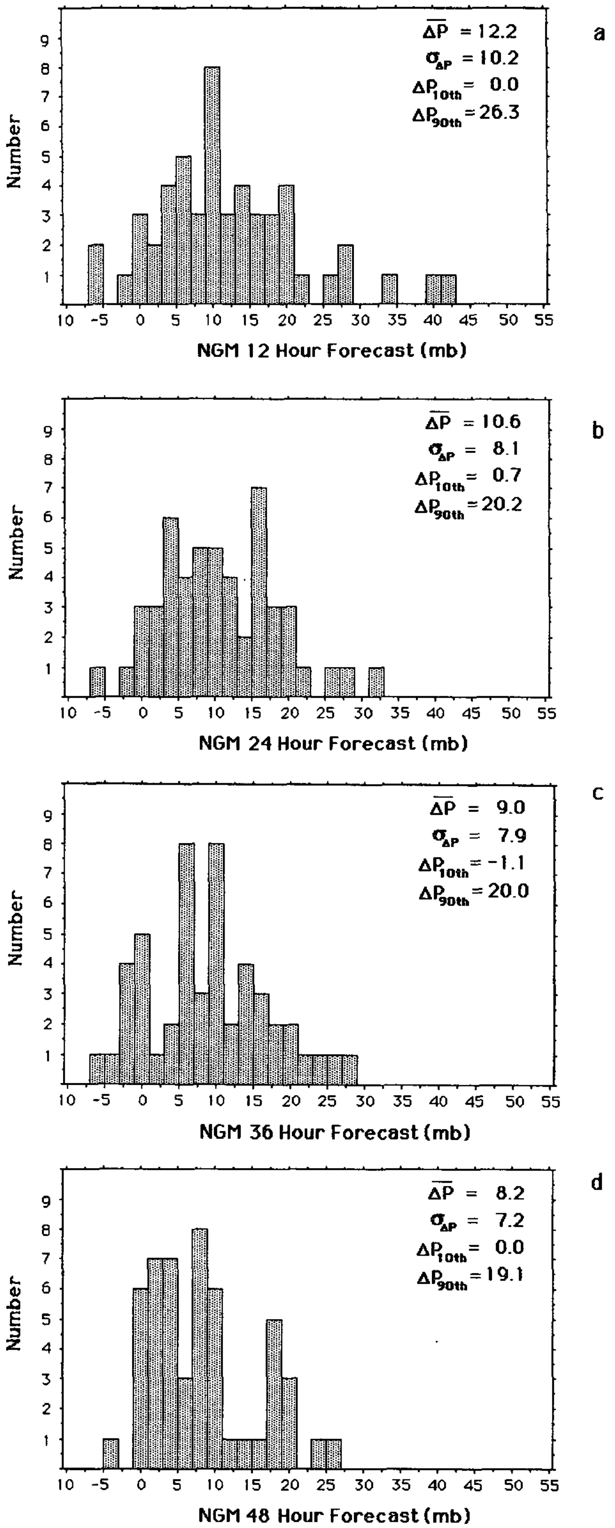


FIG. 4. Frequency plot of NGM 12-h central pressure fall for the Western Atlantic 1988–89 cold season cyclones for forecast times of (a) 12 h, (b) 24 h, (c) 36 h, and (d) 48 h. Summary central pressure fall statistics include: the mean (ΔP), standard deviation ($\sigma_{\Delta P}$), and the 10th ($\Delta P_{10\text{th}}$) and 90th percentile ($\Delta P_{90\text{th}}$) central pressure falls.

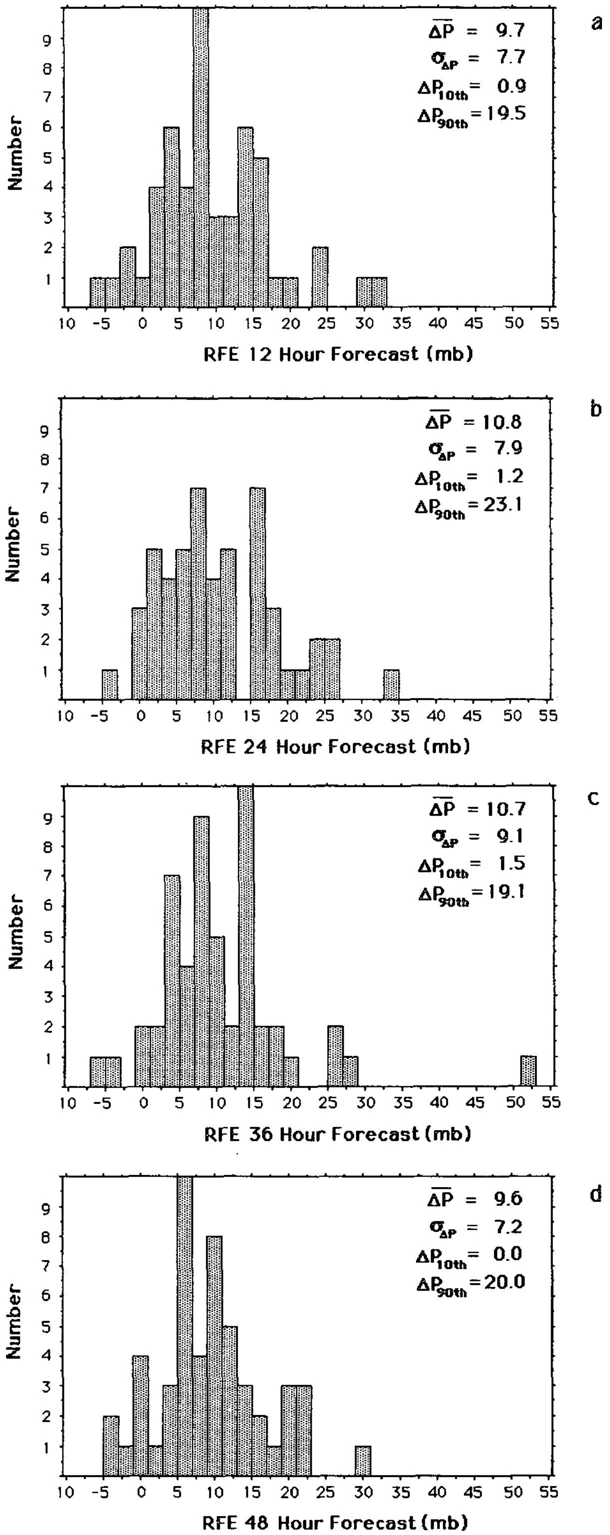


FIG. 5. Same as Fig. 4 except for the RFE forecasts.

TABLE 2. 12-h cyclone central pressure change error statistics for the Western Atlantic 1988–89 cold season. Statistics are the number of events (N), mean error ($\overline{\Delta P}$), error standard deviation ($\sigma_{\Delta P}$), coefficient of skewness (γ), coefficient of kurtosis (κ), and the number of skewness standard deviations from zero ($\Delta\gamma$).

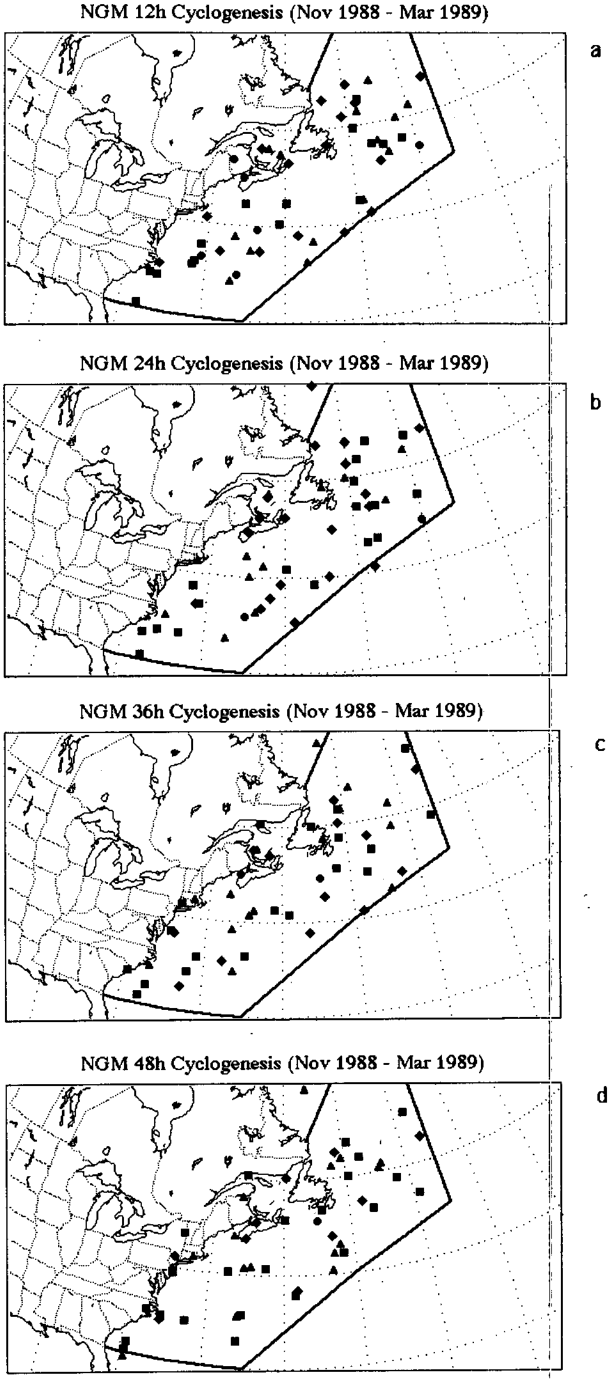
Run	N	$\overline{\Delta P}$ (mb)	$\sigma_{\Delta P}$ (mb)	γ	κ	$\Delta\gamma$
NGM 12	52	−4.8	5.5	−0.28	3.08	0.8
NGM 24	51	−6.2	6.3	−0.43	2.63	1.3
NGM 36	50	−8.1	7.9	−0.62	3.81	1.8
NGM 48	51	−9.0	8.3	−0.87	3.97	2.5
RFE 12	52	−7.3	6.2	−0.15	3.05	0.4
RFE 24	51	−6.3	6.5	−0.58	3.48	1.7
RFE 36	52	−6.3	8.1	−0.16	2.14	0.5
RFE 48	51	−7.5	7.2	−0.62	3.18	1.8

Auciello (1989), and Figs. 2 and 3 of this study demonstrate that analyzed cyclogenesis was more intense in the 1988–89 cold season, in association with an offshore storm track, as discussed in section a. The analyzed vs. predicted deepening data from Fig. 3a of Sanders and Auciello (1989) and the data from the present study reveal a strong correlation between analyzed 12-h cyclone central pressure fall and model prediction error, that is, cases with larger analyzed 12-h pressure falls are generally associated with larger model (underforecast) errors. The general tendency of numerical models to underforecast maritime cyclogenesis, first noted by Leary (1971) and most recently documented in the NGM by Grumm and Siebers (1989), exacerbated by the more difficult challenge of predicting generally more intense cyclogenesis, would seem to be the most likely explanation of the poorer performance of the NGM in the present sample.

In the RFE, there appears to be a spin-up problem at 12-h range, which shows performance levels degraded to that of the 48-h forecasts. However, the data suggest that the RFE forecasts degrade somewhat less rapidly with time than the NGM, starting from nearly equivalent performance levels at 24-h range. Comparison of these results with past cold seasons is not possible for the RFE model, because performance studies similar to those conducted with the NGM have not appeared in the literature.

The coefficient of kurtosis measures the peakedness of a distribution (the normal distribution has a coefficient of 3.0). A distribution with a high kurtosis indicates that relatively many cases occur near the mean, while a distribution with a low value is manifested by a flatter histogram, with relatively more cases falling at the extremes. In numerical guidance that consistently increases in accuracy with decreasing forecast range, one might expect to see some tendency towards a "bunching" of errors near the mean, and a corresponding increase of kurtosis. However, the data of Table 2 demonstrate that this is not the case in either model.

Figures 6 and 7 show the model (NGM, RFE) cyclone position forecasts for the four forecast ranges. At 12 and 24 h, the NGM captures reasonably well the


NGM 12h Cyclogenesis (Nov 1988 - Mar 1989)

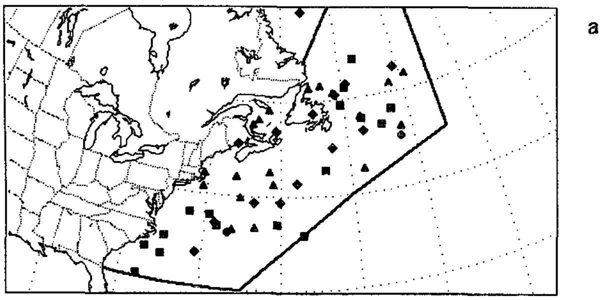
NGM 24h Cyclogenesis (Nov 1988 - Mar 1989)

NGM 36h Cyclogenesis (Nov 1988 - Mar 1989)

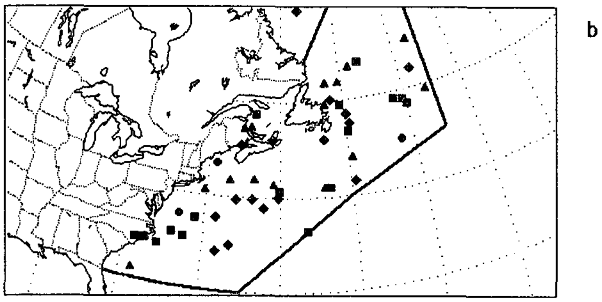
NGM 48h Cyclogenesis (Nov 1988 - Mar 1989)

FIG. 6. NGM forecast maximum deepening positions of Western Atlantic 1988–89 cold season cyclones for forecast times of (a) 12 h, (b) 24 h, (c) 36 h, and (d) 48 h. The bold line indicates the study boundary, and the symbols correspond to forecast 12-h cyclone central pressure falls of less than 6 mb (■), 6–12 mb (▲), 12–24 mb (♦), and greater or equal to 24 mb (●).

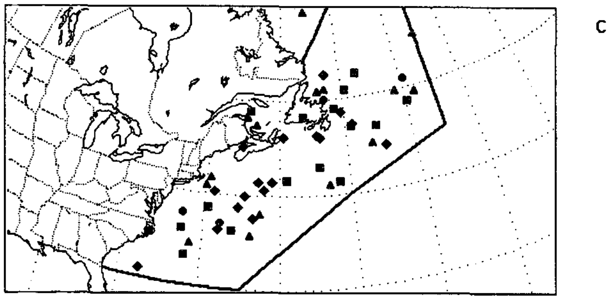
RFE 12h Cyclogenesis (Nov 1988 - Mar 1989)



RFE 24h Cyclogenesis (Nov 1988 - Mar 1989)



RFE 36h Cyclogenesis (Nov 1988 - Mar 1989)



RFE 48h Cyclogenesis (Nov 1988 - Mar 1989)

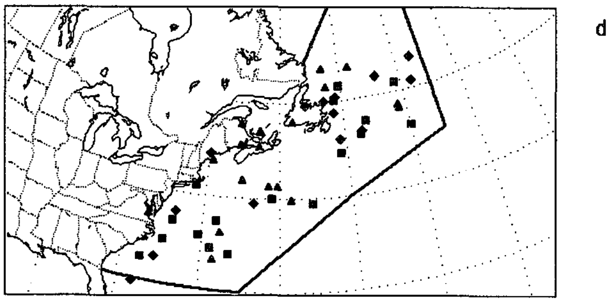


FIG. 7. Same as Fig. 6 except for the RFE forecasts.

offshore cyclone track (Fig. 3), while the magnitude of the events (as discussed above) are somewhat underrepresented. In contrast, at 36 and 48 h, the model cyclones are weakened and scattered to the extent that it is difficult to define a primary cyclogenetic zone. This can be quantified by counting the number of cyclones with a maximum deepening position within the latitude–longitude band 35–40°N and 55–75°W, a region of concentrated cyclogenetic activity in the analysis (15 storms). The NGM at 12-, 24-, 36-, and 48-h range produced 13, 13, 7, and 5 storms, respectively, in this region. These results indicate that the NGM tends to lose "precision" with increasing temporal range, in terms of both the position and magnitude of cyclogenesis. The behavior in the RFE is more complex. Counts in the same latitude–longitude band for the RFE at 12-, 24-, 36-, and 48-h ranges are 13, 10, 11, and 9 storms, respectively. The offshore cyclogenesis zone is generally maintained, but with varying success that does not degrade monotonically with increasing temporal range. There is a tendency in the model to produce cyclogenesis farther inshore than was analyzed, a feature most evident at the 24- and 36-h ranges.

Figure 8 shows the lagged forecast ensemble mean absolute error in maximum 12-h cyclone central pressure fall as a function of the ensemble error standard deviation for each of the models; the plots thus indicate the accuracy of the set of successive forecasts of 12-h cyclogenesis along the ordinate and the variability of those forecasts along the abscissa. These statistics were computed over the ensemble of (usually) four forecasts for each of the 52 cases. Due to missing data, four of the NGM and two of the RFE ensembles were comprised of three forecasts. These points are indicated by squares in Fig. 8. One might expect to see a strong relationship between the ensemble mean absolute error and the ensemble error standard deviation (as demonstrated by a high value of the square of the correlation coefficient, R^2), because the accepted (and operational) view is that consistency in a sequence of model forecasts indicates reliability (e.g., Reed et al. 1988). However, these results show that *the degree of variability in the forecasts is not well related to the overall prediction error,* because of the number of ensembles of low variance and high error (consistent but usually substantial underforecasts of development) and ensembles of high variance and low error (inconsistent but within range of the analyzed development).

It is worthwhile to consider the implications of this result. The conventional wisdom that examining the consistency of successive forecasts gives some measure of the reliability of the predictions appears, at least to this author, to be based largely on the examination of large scale features predicted at medium range on 500 mb charts (e.g., Tennekes 1988; Livingston and Schaefer 1989). This represents a fundamentally different scale both in space and time than that under consideration in this paper. It may well be that the conventional wisdom holds for larger scales, although little quantitative validation of this statement has appeared in the literature. The problem arises in attempting to apply this heuristic guideline to the scales important for explosive cyclogenesis. The forecasts for the ERICA IOP number two cyclone from the RFE model are illustrative. This cyclone represents one of the more ex-

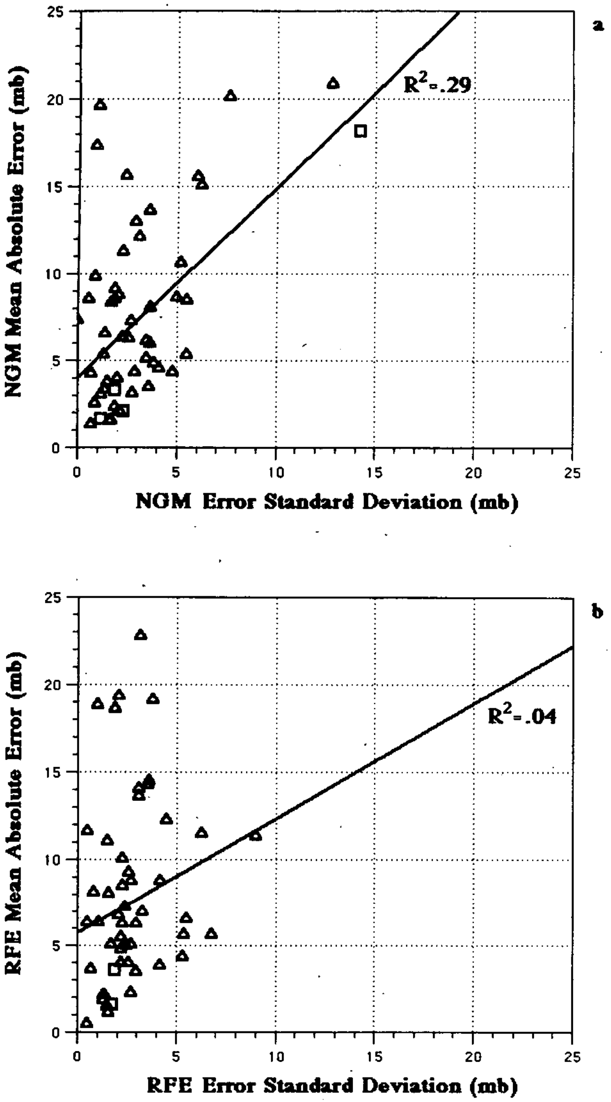


FIG 8. Ensemble mean absolute error vs. ensemble error standard deviation of (a) NGM and (b) RFE 12-h cyclone central pressure falls for the 1988–89 Western Atlantic cold season. The triangles indicate all four forecasts were available and the squares indicate only three of four forecasts were available. R^2 represents the square of the linear correlation coefficient and the solid line shows the best fit to the data.

treme cases in the 1988–89 sample, both from the point of view of analyzed 12-h cyclone central pressure fall (30 mb), and in terms of the variability of the sequence of successive 12-h model forecasts (ensemble standard deviation of 9.0 mb). Despite these substantial variations in forecast surface cyclogenesis, the 500 mb patterns in the vicinity of the surface low were quite consistent from run to run. Root mean square differences in the forecast 500 mb height fields (relative to the initial analysis at the onset of the 12-h period of rapid deepening, measured in a box approximately 20° latitude on each side) ranged from 13.6–26.2 m. Since the precision of measurement of a typical radisonde flight is on the order of 24 m (Hoehne 1980), these differences are at, or only slightly above the noise level of the analysis. It appears that, in some circumstances, accurate and consistent forecasts of the 500-mb height field are not sufficient to ensure accuracy or consistency at smaller/shorter scales. Thus, information that may prove useful at the large scale in terms of suggesting the reliability of a particular forecast regime (e.g., colder than normal, warmer than normal etc.) may not be appropriate in inferring the level of confidence in forecast details at the regional scale.

Weinstein and Sanders (1989) demonstrated that every 1 mb/h of central pressure fall corresponds to an increase of approximately 2 kt/h of the maximum sea-level geostrophic wind. We use their relationship to restate the 12-h central pressure change data for two ensembles (representing high error-low variance and low error-high variance) as the approximate increase in the maximum geostrophic wind (Table 3), in order to examine the significance of forecast variability in terms of a parameter of more direct operational utility. The high variance ensemble (21 Jan) suggests considerable wind increases at all forecast ranges, although the precise magnitude of the event is not well defined. Because storm damage increases dramatically with wind speed (e.g., Leicester and Beresford 1978), this level of uncertainty is problematic. The low variance ensemble (2 March) suggests relatively minor maximum geostrophic wind increases with a high degree of consistency between successive forecasts, contrary to the rather substantial wind increase diagnosed from

TABLE 3. Observed surface pressure (P_0) at the start of the 12-h period of intensification, estimated increase in the maximum geostrophic wind (ΔV_G) over the same interval, ensemble mean absolute error ($\mathrm{MAE}_{\Delta P}$), and ensemble error standard deviation (σ_E) for two cases from the 1988–89 cold season.

	Increase of maximum geostrophic wind (kt/12-hr)											
	Observed		NGM 0012		NGM 1224		NGM 2436		NGM 3648			
Ensemble date	P_0 (mb)	ΔV_G	P_0 (mb)	ΔV_G	P_0 (mb)	ΔV_G	P_0 (mb)	ΔV_G	P_0 (mb)	ΔV_G	$\mathrm{MAE}_{\Delta P}$ (mb)	σ_E (mb)
Jan 21 0012	992	58	997	60	998	43	998	54	1004	35	4.5	4.1
Mar 2 1200	988	56	993	18	995	13	998	18	993	16	17.3	0.9

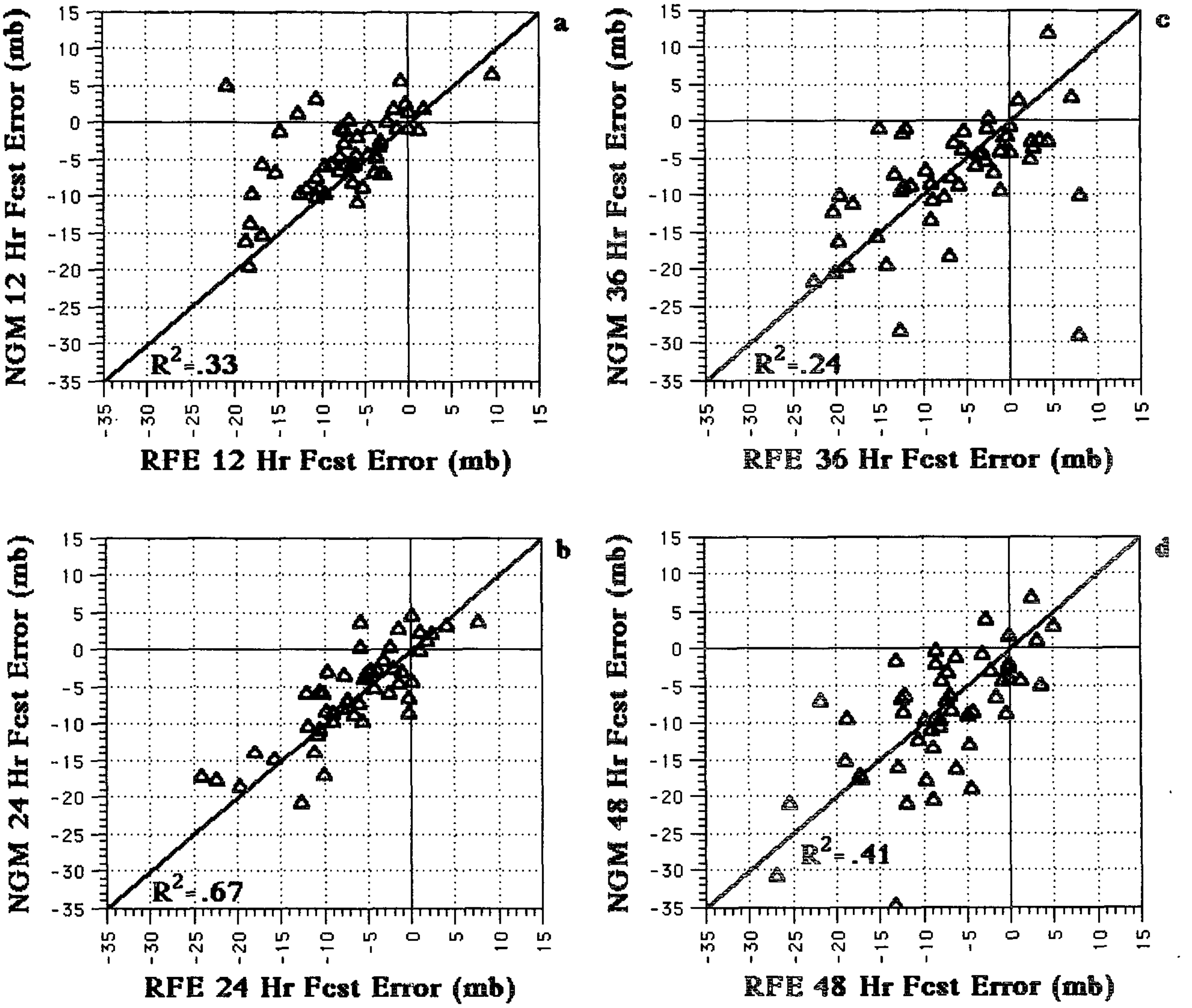


FIG. 9. Operational model cross comparisons of (a) 12-h, (b) 24-h, (c) 36-h, and (d) 48-h forecast cyclone 12-h central pressure fall errors. The one-to-one line is plotted along with R^2, the square of the linear correlation coefficient.

the analyzed 12-h intensification. Thus, the underlying causes of a *lack of variability* in an ensemble of *incorrect forecasts* is also of considerable practical interest.

c. Forecast vs. forecast

Forecasters frequently compare runs from two or more operational models, in an effort to gain some appreciation of the physical consistency represented by the model output. Specific models used will vary depending on the nationality of the forecast office, but the principle underlying approach is the same. In Canada, the operational models most frequently compared in this manner are the NGM and the RFE. Figure 9 shows cross-model comparisons of 12-h cyclone central pressure change errors for these models at each forecast range. Relative model performance is quite similar at all ranges for most cases; a substantial underforecast of cyclone development in one model is usually mirrored in the second. Thus, it would appear that in many instances that little additional information is obtained by this procedure. However, there are some notable differences in the way particular runs handle a given situation. In such instances, the forecaster must rationally discount at least one of the model forecasts. There are a number of reasons why the forecast of a cyclogenesis event might differ between models. The most obvious cause of such divergence is differences in the initial analysis. Other factors include differences in model physics, resolution, and method of solution. Unfortunately, except for gross indications of a poor initial analysis in one of the models, isolating the effect of such influences on the model forecasts in an operational setting can prove difficult. It is widely accepted that the atmosphere is a nonlinear system that exhibits strong sensitivity to initial conditions (e.g., Lorenz 1963, 1969, and 1984; Leith 1971; Tennekes 1988). It is therefore possible that model runs may diverge over short time intervals (12–48 h) as a result of *subtle* differences in the initial conditions feeding back into the evolution of the flow. This topic will be discussed further in section 4.

The question arises as to whether the two operational models perform in a similar fashion, both with regard to their mean error characteristics for a given ensemble, and the variability of the sequence of forecasts within that ensemble. Figure 10 shows cross-model comparisons of ensemble mean absolute error and ensemble error standard deviations. The results suggest that relative model performance is also similar for an ensemble of lagged forecasts in terms of the overall error, but that substantial differences in the consistency of individual forecasts within each model ensemble occur. Unfortunately, the limited relationship between consistency and reliability shown in Fig. 8 means that there is little justification for preferring one set of numerical guidance over another solely on the basis of the consistency of a sequence of forecasts. The forecaster may be left to choose between one set of forecasts consistently showing a given level of development, and a second model sequence showing a substantial range of cyclogenesis, without knowing which product is the better representation of the evolution of the flow.

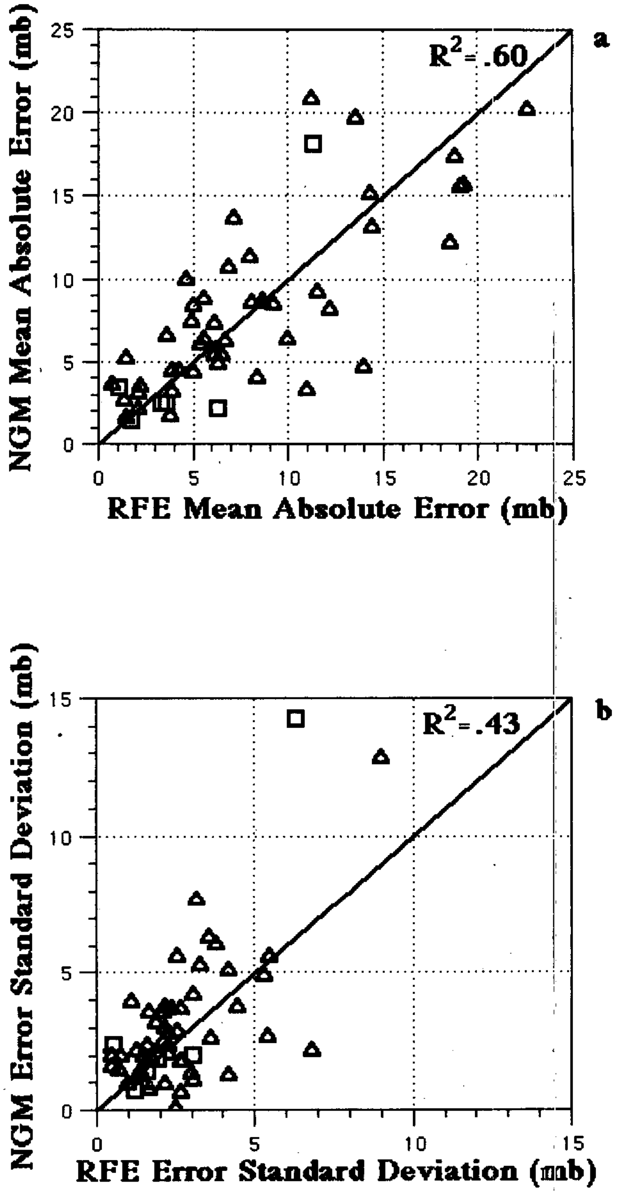


FIG 10. Operational model cross comparisons of (a) ensemble mean absolute error and (b) ensemble error standard deviation of forecast cyclone central pressure falls for the 1988–89 Western Atlantic cold season. The triangles indicate all eight forecasts were available and the squares indicate seven of eight forecasts were available. The one-to-one line is plotted along with R^2, the square of the linear correlation coefficient.

4. Discussion

Apparently, even within the bounds of successive simulations of a cyclone event over a 48-h period for which the large-scale state is presumably well known, considerable variability in model simulations of surface conditions can result. Explosive cyclogenesis is a process that can occur on a time scale of the order of 6–12 h, yet there is evidence that such sensitivity to initial conditions can be significant even in these circumstances (Anthes et al. 1983; Reed et al. 1988; Kuo and Reed 1988; Mullen and Baumhefner 1988, 1989). Indeed, Kuo and Low-Nam (1990) suggested that explosive cyclogenesis is *more* sensitive to initial uncertainties than ordinary cases. This variability suggests that, perhaps because of the complex synergism within the atmosphere (e.g., Uccellini et al. 1987; Gyakum 1987), correctly simulating particular details of the mesoscale maritime environment may be crucial to achieving further forecast gains. An example of this synergism can be understood with reference to the vorticity equation, which to first order states that the rate of increase of cyclonic vorticity is proportional to the product of the absolute vorticity and convergence (i.e., forcing of vertical motion). Thus, for a given magnitude of synoptic scale forcing (which, quasi-geostrophically is represented by differential vorticity advection and the Laplacian of temperature advection or, alternatively, convergence of Q-vectors; see Hoskins et al. 1978), the surface spin-up will be proportionately larger if the low-level vorticity has been enhanced prior to interaction with the mobile 500-mb trough, perhaps by frontogenesis, surface fluxes, or precipitation processes.

It is of considerable scientific and operational interest to understand this variability, and to document the temporal and spatial scales at which this variability is important. An understanding of this variability would likely lead to considerable physical insight. The availability of successful model simulations in combination with the enhanced data sets available through ERICA suggest new opportunities to obtain a more comprehensive physical understanding of the nature of maritime cyclogenesis.

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