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ON THE CONTRIBUTION TO MODEL-FORECAST VERTICAL MOTION FROM QUASI-GEOSTROPHIC PROCESSES

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1. INTRODUCTION

In a recent paper, Barnes (1986) presented a case study in which significant differences were noted between the vertical motion explicitly forecast by the National Meteorological Center's Limited-Area Fine-Mesh Model (LFM) and the quasi-geostrophic (QG) forcing for vertical motion as calculated from the model-predicted height fields. For the day in question, it turned out that the QG forcing diagnosed from the LFM 12-hr forecast height fields would have been a much more accurate predictor of the ensuing convective weather than the model-forecast vertical motion available as forecaster guidance. As he notes in his discussion "...when a numerical model that incorporates a more sophisticated treatment of the physical causes for vertical motions significantly departs in its prediction from motions that are geostrophically forced, then one would hope that it does so in the direction of more accurately predicting those motions with regard to the ensuing weather [original emphasis]." In the case Barnes presented, it appeared that the LFM failed to meet that expectation.

Several questions arise from consideration of the Barnes case. For instance, how frequently do significant departures arise between model-predicted vertical motion and that inferred from QG forcing? When substantial departures do exist, can one generalize about which version is more nearly correct with regard to the ensuing weather? On what physical basis and under what synoptic situations do these differences develop? How well do numerical models predict QG diagnostic fields? Does the initialization process have any impact on the differences? Finally, and most importantly for the field forecaster, the LFM has been replaced operationally by the Nested Grid Model (NGM) since the Barnes study; might it also be prone to the same behavior? Do the two models have different characteristics with respect to these issues?

2. METHODS AND DATA

In 1987, a field experiment called DOPLIGHT '87 was conducted in Oklahoma, from 15 March to 15 June (see Forsyth et al., 1988). During the experiment, considerable effort was made to document the QG diagnostic fields with the routines developed by Barnes (1985) using the twice-daily rawinsonde observations as input. We since have acquired all available model-generated height and vertical motion fields for the same period, and are comparing the QG forcing for vertical motion as diagnosed from the height fields to the model-predicted vertical velocities. We have initial and forecast fields at 6 hr intervals through 48 hrs for the 0000 UTC and 1200 UTC runs of both the LFM and NGM, although we have discovered that the initial vertical motion fields for both models and the LFM 300 mb initial height fields are not archived. Since the Barnes routines use mean heights between mandatory levels to infer the QG diagnostics nominally at intermediate levels, the absence of the LFM initial 300 mb height fields means that we cannot produce the 400 mb diagnostics at the initial time. To obtain the 400 mb LFM forecast diagnostics, we were able to reconstruct 300 mb heights hydrostatically from other archived data, but this was not possible for the initial fields. Generally, we produce the same diagnostics as in the Barnes (1986) study, except that we have more than 90 days of two-per-day forecast output at 6-hr intervals.

Given that we can produce QG diagnostics from the model-predicted height fields, how do we compare these with the explicit vertical motion forecasts? The most direct approach might be to use the model-predicted diagnostics as input to solve the QG "omega equation" for the vertical velocities. However, this introduces the complication of having to deal with boundary conditions of dubious validity, especially on the lateral boundaries. Moreover, it would entail considerable computational expense to solve the omega equation. Like Barnes, we have chosen rather to compare the Q-vector divergence [divQ -- see Hoskins et al., 1978] fields to the vertical velocity fields [VV]. Care must be taken in doing so because the vertical motion inferred from QG diagnostics must account for vertical coupling in the omega equation (Durran and Snellman, 1987).

We also have chosen primarily to rely upon satellite images to serve as "verification" for the forecasts, again in keeping with the Barnes study. While this method does not give a complete picture of the true vertical motion field at all levels, it should give a fairly accurate representation of the areas of strongest subsidence and ascent, except where there are regions of ascent in either extremely dry air or within layers which are insufficiently deep to allow air parcels to be lifted to saturation.

Our viewpoint is primarily that of a forecaster attempting to interpret numerical model output in the process of making a forecast. Our comparisons and interpretations are subjective, at least in the current, exploratory phase of our research. Nevertheless, the field forecaster likewise is required to make many subjective judgments concerning the utility and correctness of the guidance products available to him.

Although our research is still in its early stages, even our preliminary results appear to offer some tentative answers to the questions raised by the Barnes case. Before proceeding to discuss some of these results, we recognize that QG diagnostics are most meaningfully applied on the synoptic scale. Therefore, we expect the best agreement between model-forecast and QG-inferred vertical motion when dealing with synoptic-scale weather systems uncontaminated by processes not relevant to that scale of flow. The success of QG theory in explaining much of the dynamics of large-scale weather systems leads us to concur with Barnes: significant departures from QG theory in large-scale numerical model forecasts of vertical motion are due cause for careful examination of the reasons for those departures. Thus, we are suspicious of generalizations from a limited number of cases. Even though we will offer such generalizations, we emphasize that they are offered as tentative hypotheses from what is in fact an early exploration of this topic. By the time of the conference, we expect that our study should be more advanced than at present and additional results should be available for presentation.

3. PRELIMINARY RESULTS

At the time of this writing, we have limited our attention to the 12-hr forecasts and have looked at the model runs from 15 March at 0000 UTC to 28 March at 0000 UTC. Thus, the forecast products we have examined are valid from 15 March at 1200 UTC to 28 March at 1200 UTC. This is only about 15% of our total data set, but it is possible to see certain clear tendencies even from this limited sample. Unfortunately, space limitations in this paper preclude us from providing careful documentation of all of our assertions about the results.

To begin with, it certainly appears that the case Barnes documented is not an isolated instance of disagreement between the model-predicted VV and divQ fields. We have found numerous examples where the VV forecast differed substantially from that inferred from divQ. One might ask once again how we compared these different fields. Certainly, the phase difference between divQ and VV is significant, but what about the magnitudes? Clearly, since divQ and VV are different quantities, the magnitudes are not directly comparable. Nevertheless, the magnitudes of relative maxima and minima within the fields themselves gives some sense of how much emphasis is placed on these values by the model.

The table of Fig. 1 summarizes how we have chosen to classify the degree of correspondence found between the two fields

1. EXCELLENT-TO-GOOD	2. GOOD-TO-MEDIOCRE	3. MEDIOCRE-TO-POOR (physical causes)[1]	4. MEDIOCRE-TO-POOR (sampling problems)[2]	5. MEDIOCRE-TO-POOR (reasons unknown)
12Z 20 MAR	00Z 15 MAR	12Z 16 MAR (a)	12Z 15 MAR (b)	00Z 22 MAR
00Z 21 MAR	00Z 16 MAR	00Z 17 MAR (a)	12Z 19 MAR (a)	12Z 25 MAR$^+$ [NGM]**
12Z 23 MAR*	00Z 20 MAR	12Z 17 MAR (a)	12Z 21 MAR (b)	12Z 26 MAR**
00Z 24 MAR*	12Z 22 MAR	00Z 18 MAR (a)		00Z 27 MAR$^+$ [NGM]
00Z 27 MAR$^+$ [LFM]	12Z 24 MAR	12Z 18 MAR (d)		00Z 28 MAR$^+$ [LFM]
12Z 27 MAR$^+$ [LFM]	00Z 25 MAR	00Z 19 MAR (c)		
	12Z 25 MAR$^+$ [LFM]**	00Z 23 MAR (a)		
	00Z 26 MAR**	12Z 27 MAR (a)$^+$ [NGM]		
		00Z 28 MAR (a)$^+$ [NGM]		

*good fit despite presence of convection.

**weakly-forced case.

$^+$LFM and NGM differ in evaluation of divQ and VV fields.

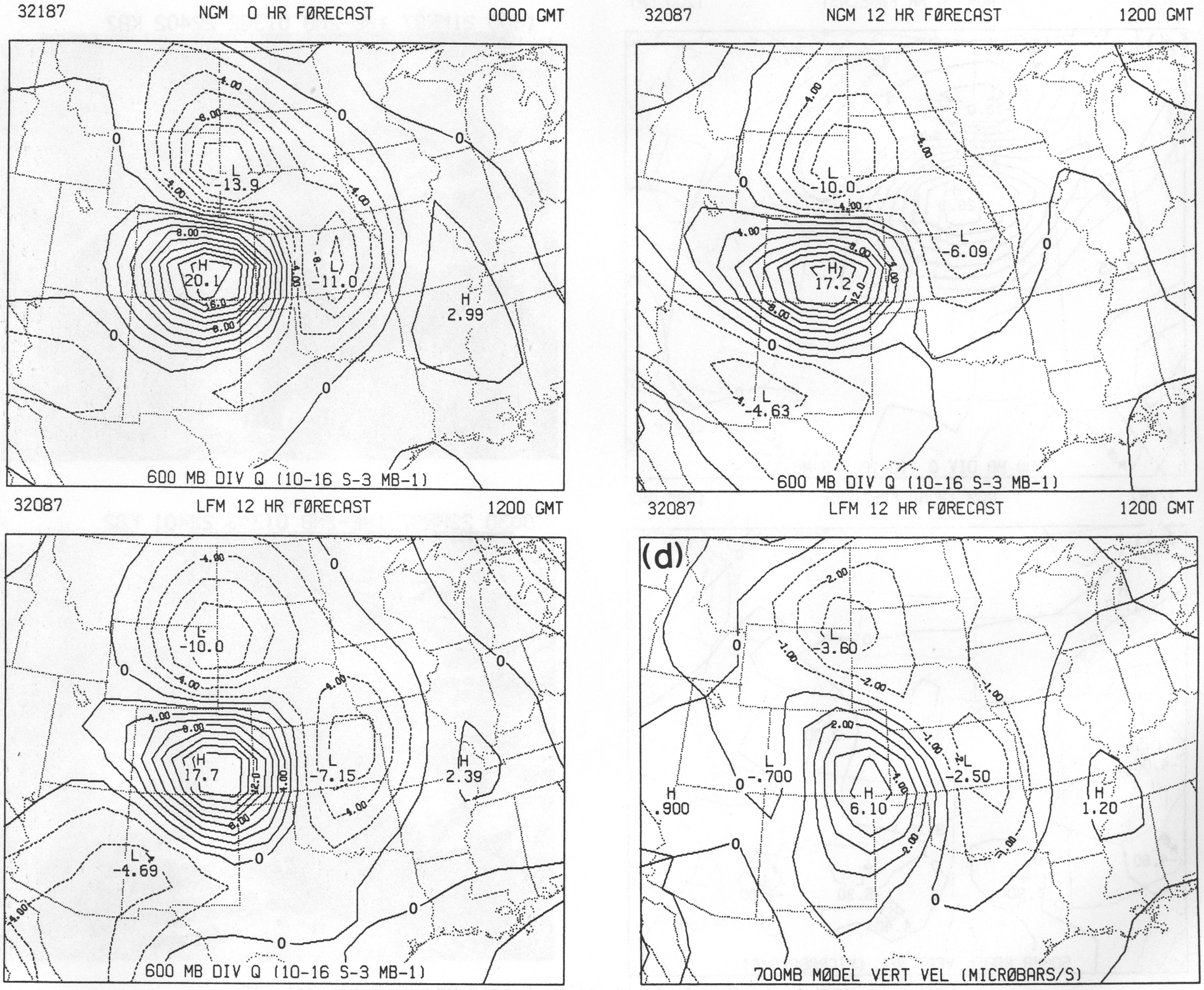
[1] physical causes include: (a) runs where model convective physics package was invoked, (b) slope flows, (c) persistent convection effects, and (d) which denotes combination of (a) and (b) or (b) and (c) above.

[2] sampling problems include: (a) systems over data void regions, and (b) systems too small to resolve.

Fig. 1 classification of model runs evaluated thus far in terms of the degree of correspondence between divQ and model-predicted VV fields. Columns 1 and 2 list runs (valid 12 hrs later) for which fit is quite good, while others list runs with poor fit for indicated reasons.

for the model runs we have analyzed thus far. The first two columns of this table list model runs for which we deem the agreement between divQ and VV to be excellent or quite good (column 1), and cases for which the agreement is somewhat poorer but still acceptably good (column 2). Of special interest are the last three columns of the table which give the model runs for which there are significant differences between the two fields. Generally, the differences between the divQ and VV depictions of the vertical motion have, so far, appeared to fall into these categories: situations where the differences were due to physical causes such as up- or down-slope-induced VV, or the model's convective physics package was invoked (column 3); situations where the observation network has caused problems with the detection and sampling of weather systems (column 4); and situations in which the reasons for the differences were not at all apparent (column 5).

Before proceeding to discuss cases for which the models produced divQ and VV fields which were dramatically different, we offer the case valid at 0000 UTC on 21 March, which is representative of the class of runs for which we consider the fit between the fields to be excellent. Some examples of the fields from this forecast are shown in Fig. 2. On this occasion, both the LFM and NGM forecasts of divQ and VV were quite similar and, perhaps not accidentally, the forecasts fit the observed weather remarkably well. In fact, this run as well as the one valid 12 hrs later produced the best forecasts during the period studied so far. Moreover, on these occasions, the models showed excellent internal agreement between the 12 hr divQ forecasts and the initialized divQ fields (i.e. the 0 hr "forecasts") valid at the same time. They also agreed quite well with the divQ fields diagnosed from the rawinsonde data. Considered in isolation, these cases might suggest that the models



<u>Fig. 2</u> NGM initialized 600 mb divQ (a), NGM forecast 600 mb divQ (b), LFM forecast 600 mb divQ (c), and LFM forecast 700 mb VV (d), all valid at 0000 UTC 21 March 1987. The LFM initialized 600 mb divQ and NGM forecast 700 mb VV are similar to their other model counterparts, except in detail, and are not shown.

fit the QG diagnostics rather well. However, this high degree of coincidence between the QG diagnostics and model-forecast VV is the exception, not the rule. It is likely significant that the above case for which DivQ and VV compare so well is also one which is characterized by a weather system that is well sampled on the synoptic scale and is not influenced by widespread, long-lasting convection or terrain effects. In contrast, a system [not shown] which moved through the domain from the data-sparse regions of the eastern Pacific and old Mexico at 0000 UTC on 20 March showed a far inferior match between divQ and VV, and the overall quality of the forecasts was much less than that seen in Fig. 2.

Yet another system observed during this period was dominated by extensive, long-lasting convection. It moved through the domain from 17-19 March and was accompanied by rather chaotic behavior with respect to the relation between divQ and VV. The erratic behavior commenced as the convection became extensive and the problem continued for one or two forecast cycles after the convection dissipated. Apparently, both the LFM and NGM can have difficulty absorbing the influences of convective physics while attempting to treat large-scale systems. In view of the relative simplicity of numerical model convective schemes, particularly in the LFM, this is not surprising. However, this behavior clearly does not result in all such cases. Despite the presence of a similar convective system on 24 March, both models nevertheless produced forecasts of divQ and VV which agreed quite well with each other and with the observed weather. At present, we cannot find an obvious explanation for the models' different behavior in the two situations.

Examples from still another storm system are shown in Fig. 3. This case

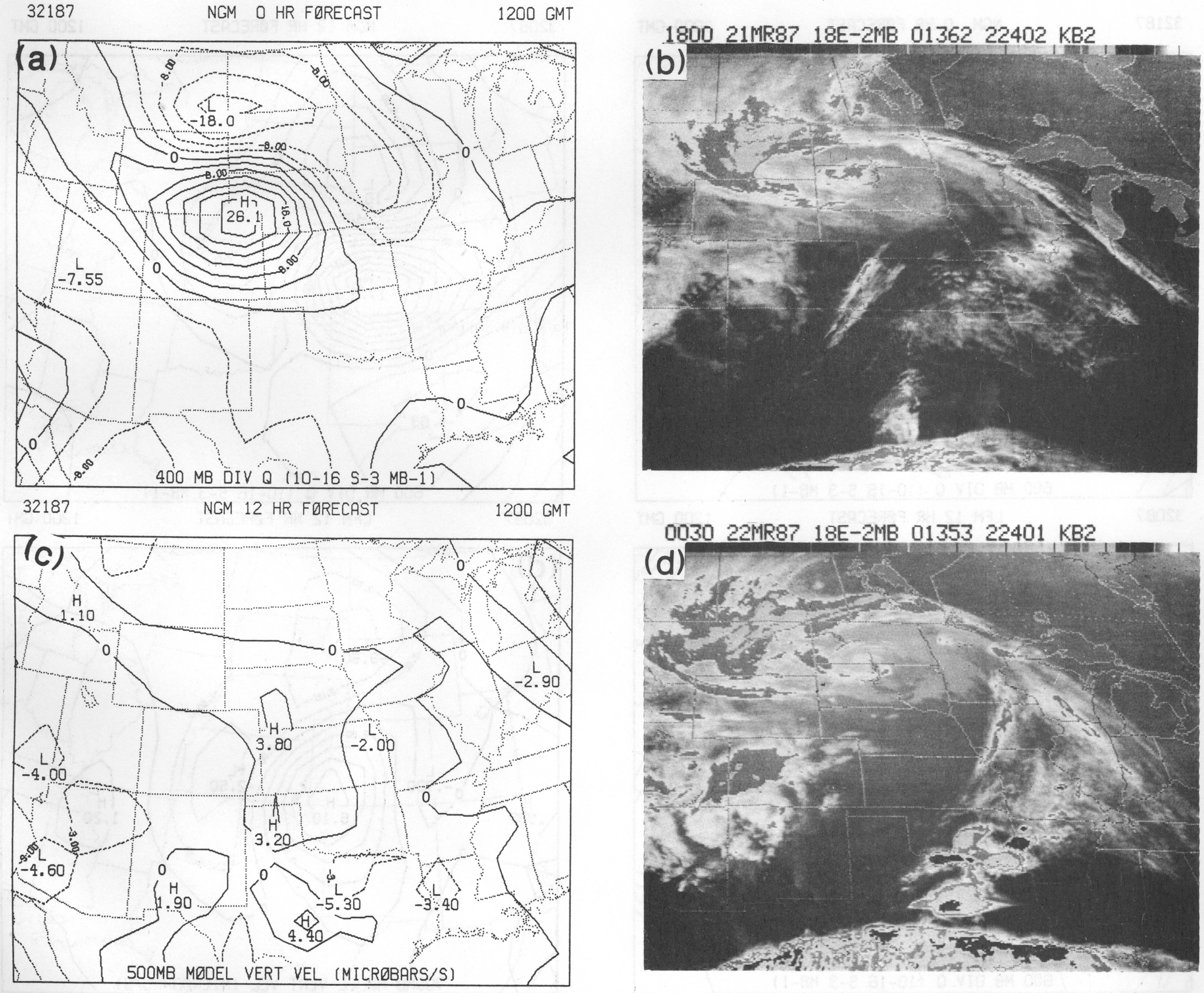


Fig. 3 NGM initialized 400 mb divQ at 1200 UTC 21 March (a), IR satellite image at 1800 UTC 21 March (b), NGM forecast 500 mb VV field valid at 0000 UTC 22 March (c), and IR satellite image at 0030 UTC 22 March (d). The clouds in eastern Colorado seen in (b) were present over southern Utah at the time of (a) and are clearly related to the events seen in (d).

involves a short-wave trough of 0000 UTC 21 March that apparently is poorly sampled by the rawinsonde network and may not be very consistent with QG theoretical assumptions. It appears that the initializations have filtered this system entirely from both models [the NGM initialization is shown] and so both the LFM and NGM predictions do a poor job of reflecting its presence. Interestingly enough, the QG diagnostics produced from the rawinsonde data [not shown] seem capable of detecting the system despite its small scale, although its phase and amplitude are not depicted with great fidelity. The fact that it was a significant system with respect to the development of convection seems to suggest that a proper model initialization should be able to recognize the presence of such subsynoptic-scale circulations if an adequate short-range (i.e. 12 hr) forecast relevant for convective development is expected.

We have found three additional model runs of the Barnes (1986) type for which the forcing for vertical motion was rather weak. These are indicated in Fig. 1 by double asterisks. Like the Barnes case, these three runs also produced VV forecasts which did not correspond very well with those of divQ. (Although we have placed two of these runs in the second category, they were characterized by the poorest fit seen among others in that category.) Generally, the VV fields for these runs were rather noisy, and poor or marginally acceptable in terms of their agreement with the observed weather.

It also has become clear that the LFM and NGM do not always behave identically in terms of their predictions of vertical velocity and the role of QG diagnostics in them. We have already found four model runs for which the two models differ appreciably in the degree of agreement between their divQ and VV fields. (We have listed these runs twice in Fig. 1, assigning each model separately to columns according to the criteria discussed above and indicating the specific model in square brackets.)

A dramatic example of differences between models occurred on 27 March in the run valid at 1200 UTC. Fig. 4 shows some examples of the fields from this run, as well as a satellite image taken at that time. Quite surprisingly, it is the <u>LFM</u> which has the superior fit between the two fields and, perhaps not altogether unexpectedly given the results discussed previously, seems to have made a substantially better VV forecast than the NGM. This behavior continued in the model run valid 12 hrs later at 0000 UTC 28 March [not shown]. This is even more remarkable when one considers that the LFM has a somewhat coarser spatial resolution than the NGM, and the system over the northern Rockies is obviously characterized by a wavelength which is on the short end of the synoptic scale.

Similar behavior was observed in the LFM forecasts valid at 0000 UTC 26 March [also not shown], although somewhat less dramatically. As noted in the table, this example was characterized by weak forcing on the synoptic scale. While not outstanding, the LFM appeared to show better correspondence between its divQ and VV fields than the NGM, and again it made the preferable forecast with respect to the observed weather. While this case taken alone seems to suggest that the LFM may handle weakly-forced situations somewhat better than the NGM, the overall trend is still that these situations seem to result in poorer forecasts by both models.

4. SOME FINAL DISCUSSION

Thus far, even our preliminary examination of the data suggests that answers to the questions we posed can be derived from the process we are following. Even with the completion of this study, however, there are important questions that will be left unanswered. For example, our study is confined to the spring season: to what extent are our results dependent on the time of year? As mentioned previously, our method of using satellite images for determining the "correctness" of the forecasts has numerous flaws -- a better approach would be to calculate the observed vertical motion by a method independent of the model or the QG diagnostics, perhaps with an integration of the continuity equation using observed winds. If one were to integrate the QG omega equation to get vertical velocities (instead of using divQ to infer the patterns) it might be feasible to determine objectively the pattern correlation between QG-forced and model-predicted vertical motion.

The issue of initialization also seems to be ripe for further study. The need to incorporate consistent information concerning subsynoptic-scale processes into numerical models is clear. This requirement is compounded by the problems of data-sparse regions and the model "memory" currently built into initialization schemes (i.e., the forecast from a previous model run is an important contributor to the initialization of the new model run). It appears that this aspect of model initialization can prolong the negative impact of poor input forecasts and noise-producing, internal model processes (e.g., convective feedback).

It is worth noting that model performance in the preceding forecast run is not necessarily a reliable guide to its current performance. We have already seen a number of cases in which the models were handling the observed weather rather well, only to have their performance suddenly deteriorate on a succeeding run for no obvious reason. On the other hand, the models also have been seen to suddenly "lock in" to the weather situation and produce a reasonable forecast after a series of questionable ones.

Finally, although our tentative ideas must be subjected to further testing by completing this work, it certainly appears to us that QG diagnostics are a worthwhile addition to any model output diagnostics package. When the models are internally consistent (divQ and VV are similar) and

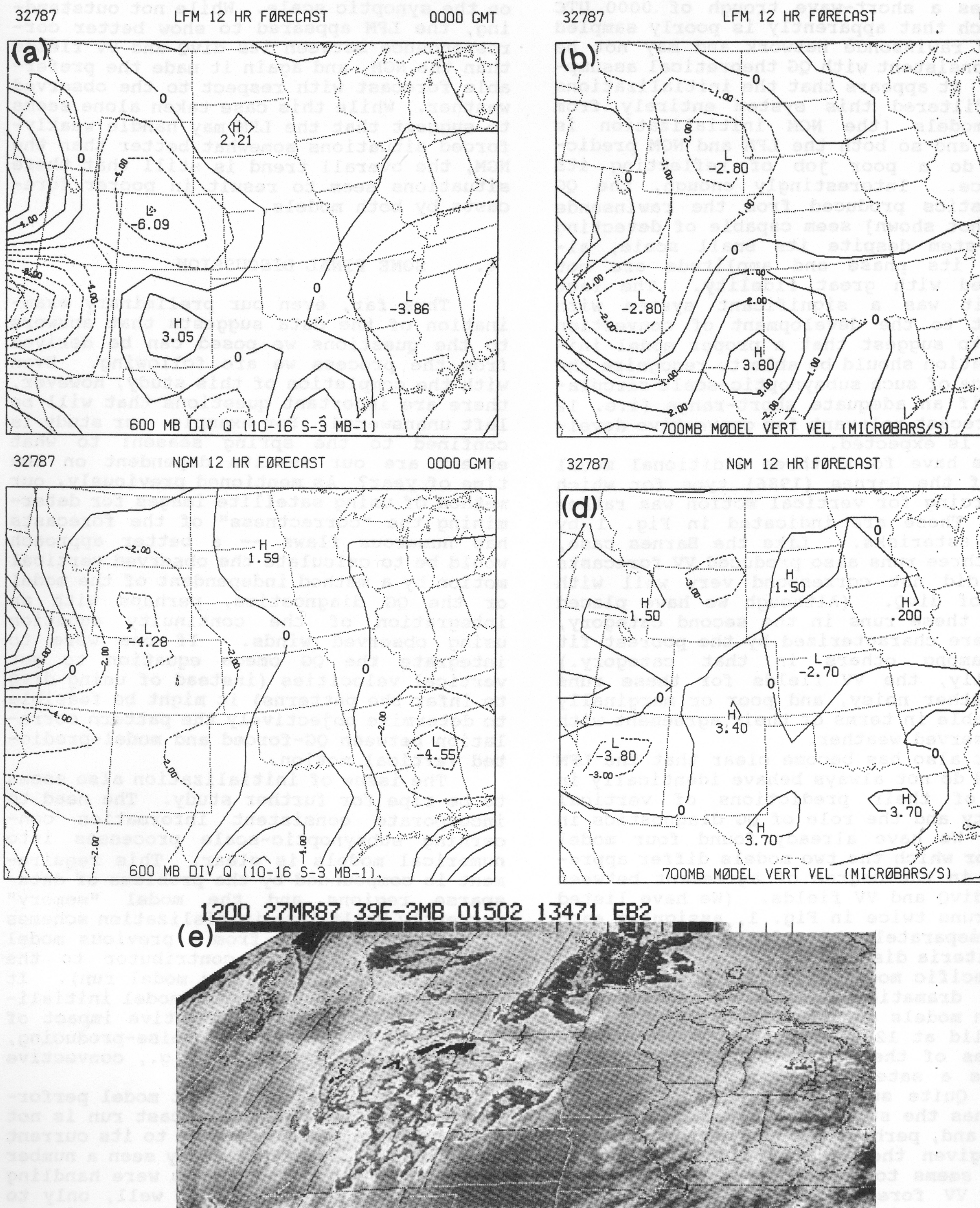


Fig. 4 LFM forecast 600 mb divQ (a), LFM forecast 700 mb VV (b), NGM forecast 600 mb divQ (c), and NGM forecast 700 mb VV (d), all valid at 1200 UTC 27 March. IR satellite image taken at 1200 UTC 27 March (e) clearly shows short-wave over Wyoming and Colorado which is well represented in LFM forecast fields, but not nearly so well in the corresponding NGM fields.

different models share that consistency, the chances are that those occasions produce the best forecasts. However, it must also be said that the divQ field should not be construed as an infallible tool for predicting the ensuing weather -- on several occasions of disagreement, the model VV fields (either the NGM or the LFM or both) gave a somewhat better indication of the weather than that inferred from divQ. Nevertheless, armed with the knowledge of the likely physical causes of differences between QG-diagnosed vertical motion and that observed in the real atmosphere, the degree of agreement between divQ and VV should help the field forecaster determine how much confidence he should place in the vertical motion guidance given to him by the models.

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