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Synoptic-Scale and Mesoscale Contributions to Objective Operational Maximum-Minimum Temperature Forecast Errors

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ABSTRACT

Root-mean-square errors of the 24 h operational, objective, maximum-minimum temperature forecasts derived from primitive equation model predictions and model output statistics are evaluated in terms of synoptic-scale and mesoscale contributions. Eight regions of the United States are examined for the period from December 1974 through November 1976. Climatology and persistence are used for comparison. For the operational forecasts, the synoptic-scale and mesoscale contribute approximately equally to the error. On the synoptic scale, the objective predictions are significantly more accurate than persistence and climatology. However, on the mesoscale, the predictions have approximately the same accuracy as climatology for minimum temperatures and only slightly more accuracy than climatology for maximum temperatures.

1. Introduction

Sanders (1973) and Bosart (1975) have reported that, in forecast competitions at their respective universities, forecasts have shown little or no improvement in recent years. They speculated that forecasters are reaching the end of possible forecast improvements on the synoptic scale and that the remaining errors can be traced to a wide variety of unpredictable mesoscale processes. Ramage (1976) also concluded that forecasts are being limited by mesoscale processes, but he envisioned these processes as occurring in infrequent "bursts" of large magnitudes. If these authors are correct, further improvements in forecast accuracy will result from better modeling on the mesoscale, rather than further refinements on the synoptic scale. This study examines quantitatively whether or not short-term operational objective forecasts of maximum-minimum temperatures contain mesoscale information, and the contribution synoptic-scale and mesoscale processes make to the forecast error.

2. Background

Objective forecasts of maximum-minimum temperatures have been issued by the National Weather Service since 1965. Until August 1973, these objective forecasts were based upon the "perfect prog" technique (Klein and Lewis, 1970; Klein *et al.*, 1971). Since August 1973, objective forecasts have been based upon the Model Output Statistics (MOS) approach (Glahn and Lowry, 1972). Predictions are made for over 200 stations within the conterminious United States. Details of the MOS approach and the various changes are given by Klein and Hammons (1975), Hammons *et al.* (1976) and Carter *et al.* (1979).

This study uses 24 h MOS forecasts for the period from December 1974 through November 1976. The maximum temperature predictions are based upon the 0000 GMT primitive equation (PE) (Shuman and Hovermale, 1968) run with 0600 GMT surface observations when available. The minimum temperature predictions are based upon the 1200 GMT PE run with 1800 GMT surface observations when available. A change in the operational system occurred within the period examined. In July 1975, new equations, based on more years of dependent data, an increased number of potential predictors, and divided into the four meteorological seasons were introduced. Thus, 17 of the 24 months of this study had forecasts from the new equations.

3. Approach

According to Yoshino (1975), the division between mesoscale and synoptic scale is envisioned by most investigators to fall between 200 and 500 km. A division of 400 km (the PE model grid length) was used in this study. Variations in both predicted and observed daily maximum-minimum temperatures within a 400 km by 400 km box are considered to be mesoscale (or less), while daily variations of the spatially averaged maximum-minimum temperatures of the area are considered to be synoptic scale (or greater). These effects can be separated out by using a root-mean-square (rms) verification scheme.

Although the above division can be applied to any collection of stations within an area, there is no

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FIG. 1. Location of regions which were analyzed. Stars give location of stations given in Table 1. Dots give stations with MOS forecasts.

unique way to select the stations to be used in the averaging. Clearly, the more stations in the average, the more reliable the results. For this study, areas within the United States where stations with objective forecasts cluster together were picked. Eight different regions, shown in Fig. 1, were examined in order to include various climatic regimes. The stations used in each region are given in Table 1. The regions are fairly evenly distributed across the United States, and represent a variety of synoptic and mesoscale influences.

The rms error (E) for a region, found by averaging the errors at the MOS stations in the region, is given by

$$E = \left\{ \frac{\sum_{j=1}^{M} [\sum_{i=1}^{N} (P_{ij} - V_{ij})^2]}{M \times N} \right\}^{1/2}, \qquad (1)$$

where M is the number of days, N the number of stations, P_{ij} the predicted maximum or minimum temperature for the ith station and the jth day, and V_{ij} the corresponding observed maximum or minimum. Let

$$\bar{P}_j = N^{-1} \sum_{i=1}^{N} P_{ij}, \quad \bar{V}_j = N^{-1} \sum_{i=1}^{N} V_{ij}, \qquad (2)$$

where $\bar{P}_j$ and $\bar{V}_j$ are the area (synoptic) average forecast and verification for the jth day. Let

$$P'_{ij} = P_{ij} - \bar{P}_j, \quad V'_{ij} = V_{ij} - \bar{V}_j, \qquad (3)$$

where P'_{ij} and V'_{ij} are the deviations from the area-average (mesoscale) for the ith station and the jth day. From (3) we get

$$\sum_{i=1}^{N} P'_{ij} = 0, \quad \sum_{i=1}^{N} V'_{ij} = 0. \qquad (4)$$

Expanding the bracket portion of (1) and utilizing (4) gives

$$\sum_{i=1}^{N} (P_{ij} - V_{ij})^2 = \sum_{i=1}^{N} (P'_{ij} - V'_{ij})^2 + \sum_{i=1}^{N} (\bar{P}_j - \bar{V}_j)^2. \qquad (5)$$

The final equation for E^2 is

$$E^2 = \frac{\sum_{j=1}^{M} (\bar{P}_j - \bar{V}_j)^2}{M} + \frac{\sum_{j=1}^{M} \sum_{i=1}^{N} (P'_{ij} - V'_{ij})^2}{M \times N}. \qquad (6)$$

The first term on the right-hand side is the synoptic-scale error squared and the second term is the mesoscale error squared. To obtain an estimate of the importance of the two terms, the square root of each is found. For the synoptic scale this is

$$\left[\frac{\sum_{j=1}^{M} (\bar{P}_j - \bar{V}_j)^2}{M} \right]^{1/2} \qquad (7)$$

and for the mesoscale

$$\left[\frac{\sum_{j=1}^{M}\sum_{i=1}^{N}(P'_{ij}-V'_{ij})^2}{M\times N}\right]^{1/2}. \quad (8)$$

Any trend in temperatures across the region (even climatological latitudinal variations of temperature) appears as a mesoscale contribution. In the discussion that follows, it should be remembered that the total rms error is the square root of the sum of the squares of the synoptic-contribution and the mesoscale contribution.

4. Results

The MOS operational forecasts, climatology and persistence were separated into synoptic-scale and mesoscale contributions. Daily climatological maximum and minimum temperatures were obtained from the National Climatic Center (1973). Persistence was taken to be the observed maximum or minimum temperature on the day of the forecast. The contributions were examined both by season and averaged over the two years of the study period.

Since the results showed that the six regions east of the Rocky Mountains had similar characteristics, they are referred to in this paper as "eastern" regions. A seasonal plot for a typical eastern region is given in Fig. 2 (minimum temperatures for the New England region). The Southwest region had somewhat different characteristics. A plot for the Southwest region is given in Fig. 3 (maximum temperatures for the Southwest region). The Northwest region seemed to be intermediate between the eastern regions and the Southwest region.

TABLE 1. Stations used in each region.

A. New England
- Albany NY
- Boston MA
- Bridgeport CT
- Burlington VT
- Concord NH
- Hartford CT
- Portland ME
- Providence RI

B. Mid-Atlantic
- Baltimore MD
- Elkins WV
- Lynchburg VA
- Norfolk VA
- Richmond VA
- Roanoke VA
- Washington (Dulles) DC
- Washington (National) DC

C. Southeast
- Asheville NC
- Atlanta GA
- Athens GA
- Augusta GA
- Chattanooga TN
- Greenville SC
- Knoxville TN

D. Lake Michigan
- Chicago (O'Hare) IL
- Grand Rapids MI
- Green Bay WI
- Houghton Lake MI
- Lansing MI
- Milwaukee WI
- Muskegon MI
- South Bend IN

E. Great Plains
- Concordia KS
- Grand Island NE
- Kansas City MO
- Omaha NE
- Russell KS
- Topeka KS

F. Texas
- Abilene TX
- Austin TX
- Fort Worth TX
- Waco TX
- Wichita Falls TX

G. Northwest
- Astoria OR
- Eugene OR
- Olympia WA
- Portland OR
- Redmond OR
- Yakima WA

H. Southwest
- Bakersfield CA
- Daggett CA
- Fresno CA
- Long Beach CA
- Los Angeles CA
- Santa Maria CA

Table 2 gives for each region the total rms error and the synoptic and mesoscale contributions to it averaged over the study period. For both maximum and minimum temperatures in all regions, persistence has a lower total rms error than climatology. Persistence errors are large in regions with high frequencies and strong intensities of frontal and cyclonic activity, such as the Great Plains region, and small in regions with less activity, especially the Southwest region. The total rms error for MOS is much smaller than that for climatology and persistence in all regions. The improvements over persistence range from 2.25°C (Great Plains region) to 0.61°C (Southwest region) for maximum temperatures, and 1.65°C (New England region) to 0.34°C (Southwest region) for minimum temperatures. In general, improvements are greatest in regions with large persistence errors and smallest in regions with small persistence errors. Even though this fact tends to reduce the region-to-region variations in errors for MOS, largest MOS errors still occur in the Great Plains region and the smallest in the Southwest region.

The plots given in Figs. 2 and 3 show graphically that persistence does better than climatology and that MOS improves over both of them in almost all seasons. (In Fig. 3, persistence did better than MOS in the summer of 1975. Such an occurrence is unusual; in all the seasons and regions studied, only one other similar case was found.) All eastern regions have a pronounced seasonal variation in the RMS errors of MOS, climatology and persistence. Most of them have the largest total rms errors in the winter and the smallest in the summer. A few notable exceptions to this pattern are the Great Lakes and New England regions for maximum temperatures, which have the largest errors in the spring. The Southwest region has an irregular seasonal variation as can be seen in Fig. 3.

Separating the total rms error into its synoptic-scale and mesoscale terms shows that the two scales contribute differently to the total rms error. As is evident in Table 2, the synoptic contribution for climatology and persistence is much larger than the mesoscale contribution for all regions except the Southwest. This result suggests that synoptic-scale phenomena contribute more to temperature variability than mesoscale phenomena, except along the west coast.

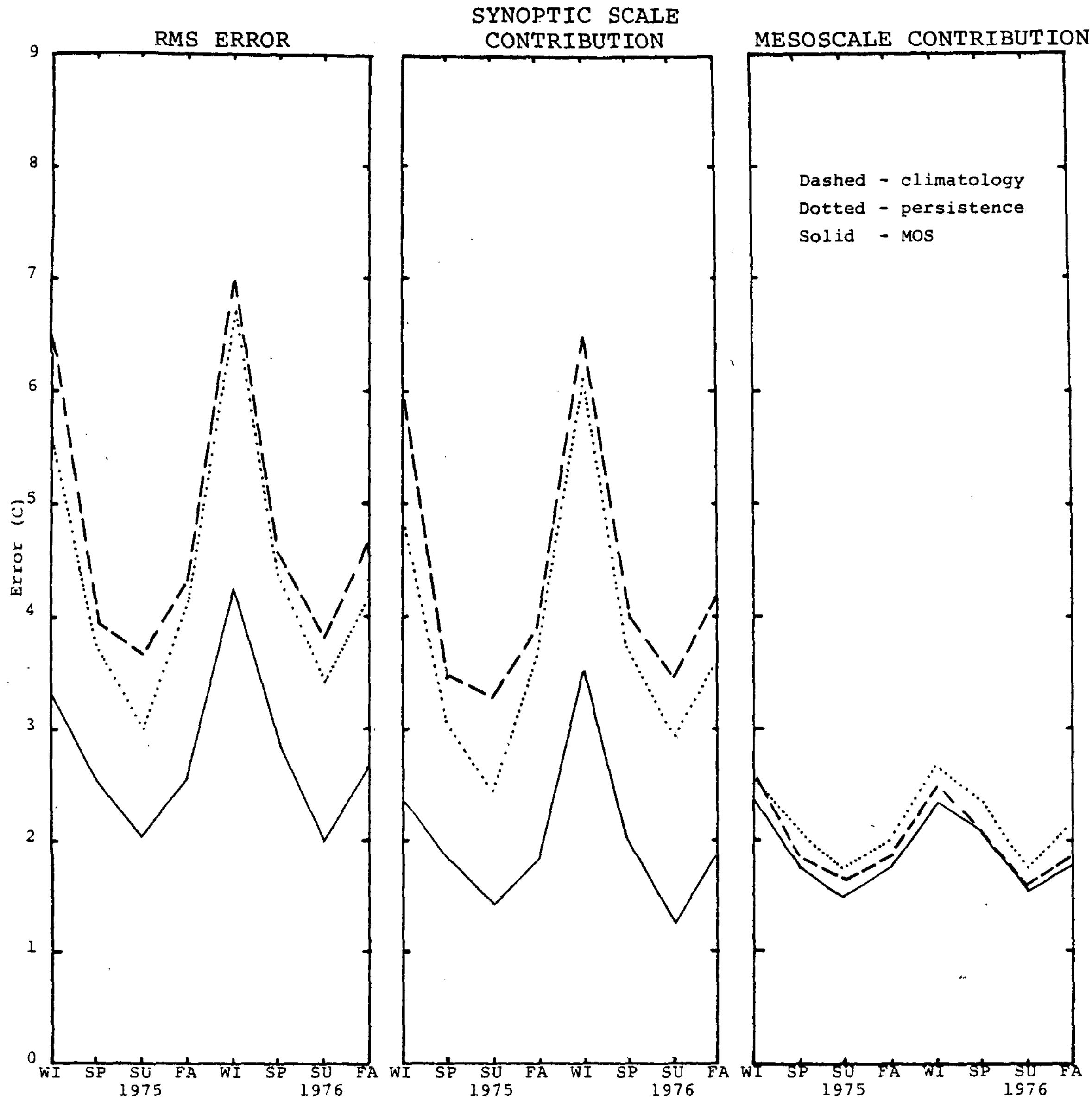

FIG. 2. Example of seasonally averaged errors for an eastern region (minimum temperatures for New England).

The overall rms errors for MOS are more equally divided between synoptic-scale and mesoscale contributions than are the errors for persistence and climatology. In all regions except in the Northwest and Southwest, the synoptic-scale contribution is larger than or approximately equal to the mesoscale. More specifically, the synoptic-scale contributions are all within 0.3°C of the mesoscale contributions for all regions except for the Great Plains region (synoptic-scale error higher than the mesoscale by 0.39°C for maximum temperatures and 0.47°C for minimum temperatures), the Southwest region (mesoscale error higher than the synoptic scale by 0.68°C for maximum temperatures and 0.38°C for minimum temperatures) and the Texas region (synoptic-scale error higher than the mesoscale by 0.35°C for minimum temperatures only).

For the eastern regions, there is a pronounced seasonal variation in both the synoptic and mesoscale errors (for example, see Fig. 2), with the largest errors in the winter and the smallest in the summer at most stations. In general for MOS, the range from summer to winter is larger for the synoptic-scale contribution than for the mesoscale contribution. The mesoscale contribution is larger than the synoptic-scale contribution in summer while the reverse is true in winter. The exception to this pattern is maximum temperature for the Great Plains region, where in

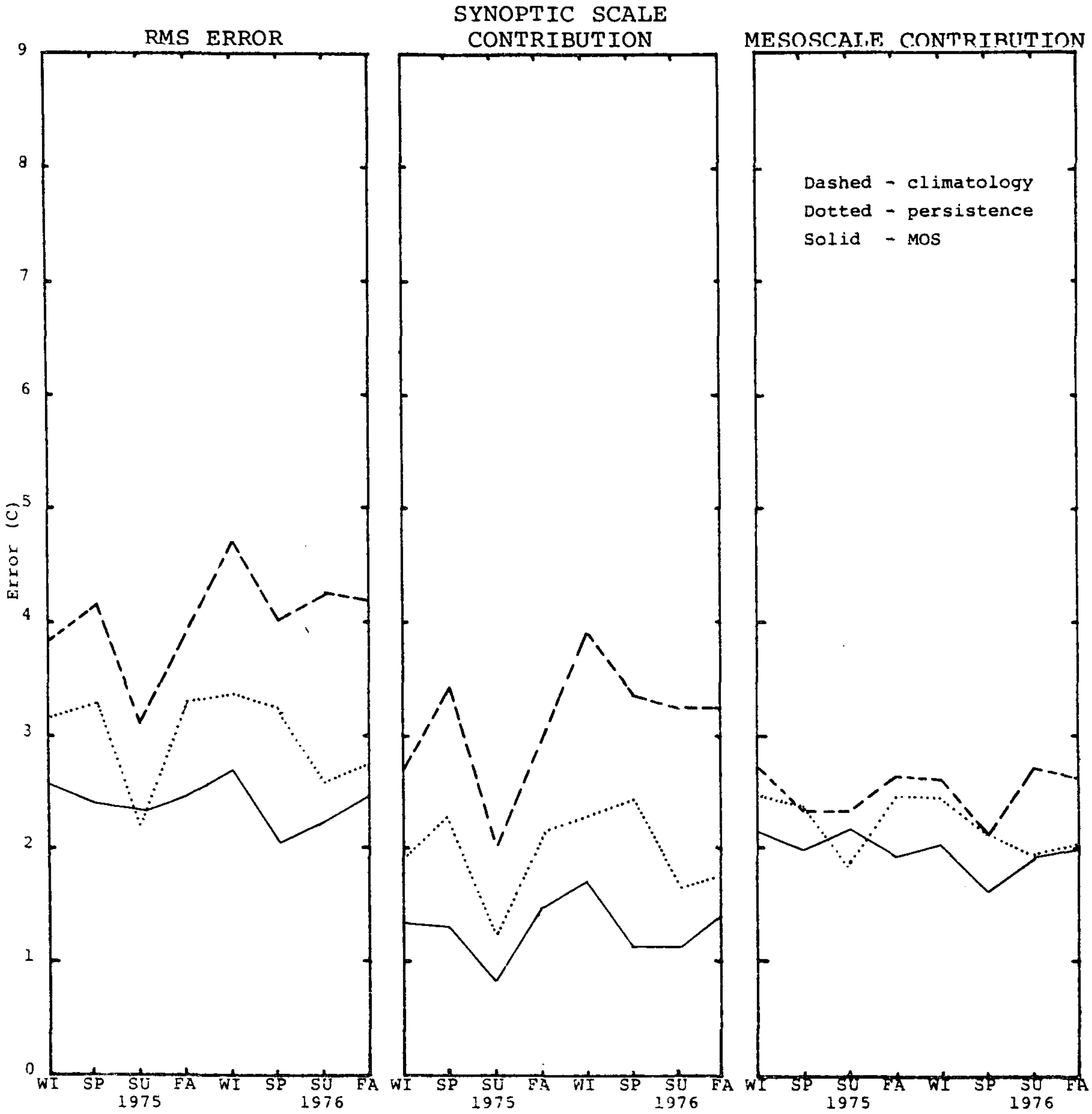

FIG. 3. Example of seasonally averaged errors for the Southwest region (maximum temperatures).

summer the synoptic-scale errors were still higher than the mesoscale errors. Apparently, for the eastern stations, in the winter MOS forecast errors tend to arise largely from the synoptic scale, while in the summer they arise largely from the mesoscale. For the Southwest region, MOS has larger mesoscale errors than synoptic-scale errors in all seasons, probably as a result of lower synoptic-scale variability in this region compared to the eastern United States.

On the mesoscale, MOS does better for maximum temperatures than either persistence or climatology for all the regions, as shown in Table 2. Improvements over the lesser of climatology or persistence range from 0.38°C for the Northwest region to 0.15°C for the Southeast and Lake Michigan regions. However, for minimum temperature forecasts, improvements are considerably smaller with four of the eight regions showing no improvement at all. The greatest improvement was 0.10°C for New England, a value which is less than the worst for maximum temperatures. Apparently, MOS forecasts for maximum temperatures contain some mesoscale information, while those for minimum temperatures contain very little mesoscale information. As shown in Figs. 2 and 3, the relative importance of the mesoscale error is not strongly dependent upon the season.

Although persistence does better than climatology on the synoptic scale, on the mesoscale for the eastern

TABLE 2. Errors (°C) for maximum and minimum temperature forecasts using climatology, persistence and 24 h MOS predictions. Given are the total rms error and the synoptic and mesoscale contributions to it.

	Maximum temperatures			Minimum temperatures		
	Total	Synoptic	Meso-scale	Total	Synoptic	Meso-scale
A. New England						
Climatology	5.07	4.65	2.02	4.91	4.47	2.02
Persistence	4.64	4.01	2.34	4.52	3.96	2.19
MOS	2.58	1.85	1.81	2.87	2.13	1.92
B. Mid-Atlantic						
Climatology	5.21	4.29	2.04	4.53	4.16	1.80
Persistence	4.70	4.03	2.41	4.02	3.53	1.94
MOS	2.53	1.83	1.75	2.46	1.75	1.72
C. Southeast						
Climatology	4.60	4.28	1.70	4.28	3.99	1.56
Persistence	3.76	3.18	2.00	3.64	3.20	1.74
MOS	2.32	1.72	1.55	2.21	1.57	1.56
D. Lake Michigan						
Climatology	5.37	5.06	1.80	5.10	4.69	2.00
Persistence	4.51	3.99	2.10	4.30	3.71	2.17
MOS	2.48	1.84	1.65	2.85	2.09	1.94
E. Great Plains						
Climatology	6.23	5.79	2.31	4.95	4.62	1.79
Persistence	5.30	4.71	2.42	4.16	3.67	1.97
MOS	3.05	2.34	1.95	2.91	2.28	1.81
F. Texas						
Climatology	5.36	4.98	1.97	4.45	4.15	1.61
Persistence	4.73	4.07	2.40	3.79	3.30	1.86
MOS	2.56	1.93	1.68	2.53	1.96	1.61
G. Northwest						
Climatology	4.13	3.46	2.25	3.47	2.94	1.84
Persistence	3.70	2.75	2.48	3.05	2.30	2.00
MOS	2.45	1.57	1.87	2.60	1.65	1.86
G. Southwest						
Climatology	3.77	3.16	2.53	3.12	2.48	1.88
Persistence	3.01	2.01	2.25	2.25	1.56	1.61
MOS	2.40	1.33	2.01	1.91	1.15	1.53

regions climatology does somewhat better than persistence. Fig. 2 shows that this relationship is not a function of season. This result suggests that, in these regions, synoptic-scale fields persist over several days, while mesoscale fields vary more from day to day. For the Southwest region, persistence does better than climatology on both the synoptic scale and the mesoscale. Apparently, in the Southwest region, mesoscale features last longer once they are established, possibly because they are more closely related to the synoptic flows than in other parts of the country.

5. Conclusions

The results of this analysis suggest that the objective operational maximum-minimum MOS temperature forecasts improve upon climatology and persistence mostly on the synoptic scale, with much less improvement on the mesoscale. The errors remaining in temperature forecasts are the result of approximately equal contributions from the synoptic scale and the mesoscale. Apparently, the operational MOS forecasts contain much more synoptic-scale information than mesoscale information. However, substantial improvements are still possible on the synoptic scale as well as the mesoscale.

This paper has dealt only with the operational guidance product available to the forecaster, not with the forecasts actually released. Statistical studies, such as that of Zurndorfer *et al.* (1979), indicate that although the local forecaster is able to improve upon guidance, the improvement has been decreasing in recent years and is now quite small. Since, according to this study, guidance contains at most a modest amount of mesoscale information, subjective forecasts probably also do not contain much more mesoscale information. Perhaps, more emphasis should be placed on mesoscale phenomena at the local forecast level.

The results of this study are based only on 24 h projections. The contributions of the synoptic scale and mesoscale are undoubtedly different at other projections. Probably, at longer projections the synoptic-scale error increases, with the mesoscale error remaining fairly constant, since the mesoscale error is already close to that for climatology and persistence. A further study similar to this one could be carried out for other projections to verify this contention.

Since improvements over climatology and persistence on the mesoscale as defined here are relatively small, especially for minimum temperatures, it appears that 400 km represents approximately the spatial limit of maximum-minimum forecasting ability for the period of this study. Cressman (1970), reporting on the work of Roberts using a spatial correlation technique, also found a limit of 400 km. It is tempting to conclude that this spatial limit results from its being approximately the mesh size of the PE model from which the forecasts originate. In this case, the current LFM operational model, which has a considerably smaller mesh size, should provide forecasts with greater mesoscale accuracy. However, the author believes that other factors, such as the density of the input data and the amount of inherent smoothing in the numerical model, are more important limiting factors. A similar study should be made using LFM forecasts to determine if improvements in the mesoscale, synoptic scale or both have resulted with the introduction of finer mesh models.

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REFERENCES

Bosart, L. F., 1975: SUNYA experimental results in forecasting daily temperature and precipitation. *Mon. Wea. Rev.*, **103,** 1013–1020.

Carter, G. M., J. P. Dallavalle, A. L. Forst and W. H. Klein, 1979: Improved automated surface temperature guidance. *Mon. Wea. Rev.*, **107,** 1263–1274.

Cressman, G. P., 1970: Public forecasting—present and future. *A Century of Weather Progress*, J. E. Caskey, Ed., Amer. Meteor. Soc., 71–77.

Glahn, H. R., and D. A. Lowry, 1972: The use of model output statistics (MOS) in objective weather forecasting. *J. Appl. Meteor.*, **11,** 1203–1211.

Hammons, G. A., J. P. Dallavalle and W. H. Klein, 1976: Automated temperature guidance based on three-month seasons. *Mon. Wea. Rev.*, **104,** 1557–1564.

Klein, W. H., and G. A. Hammons, 1975: Maximum-minimum temperature forecasts based on model output statistics. *Mon. Wea. Rev.*, **103,** 796–806.

——, and F. Lewis, 1970: Computer forecasts of maximum and minimum temperatures. *J. Appl. Meteor.*, **9,** 350–359.

——, —— and G. A. Hammons, 1971: Recent developments in automated max-min temperature forecasting. *J. Appl. Meteor.*, **10,** 916–920.

National Climatic Center, 1973: *Climatology of the United States*, No. 84 [National Climatic Center, Federal Building, Asheville].

Ramage, C. S., 1976: Prognosis for weather forecasting. *Bull. Amer. Meteor. Soc.*, **57,** 4–10.

Sanders, F., 1973: Skill in forecasting daily temperature and precipitation: some experimental results. *Bull. Amer. Meteor. Soc.*, **54,** 1171–1179.

Shuman, F. G., and J. B. Hovermale, 1968: An operational six-layer primitive equation model. *J. Appl. Meteor.*, **7,** 525–547.

Yoshino, M. M., 1975: *Climate in a Small Area.* The University of Tokyo Press, 549 pp. [ISBS, Inc., P.O. Box 555, Forest Grove, OR 97116].

Zurndorfer, E. A., J. R. Bocchieri, G. M. Carter, J. P. Dallavalle, D. B. Gilhousen, K. F. Hebenstreit and D. J. Vercelli, 1979: Trends in comparative verification scores for guidance and local aviation-public weather forecasts. *Mon. Wea. Rev.*, **107,** 799–811.