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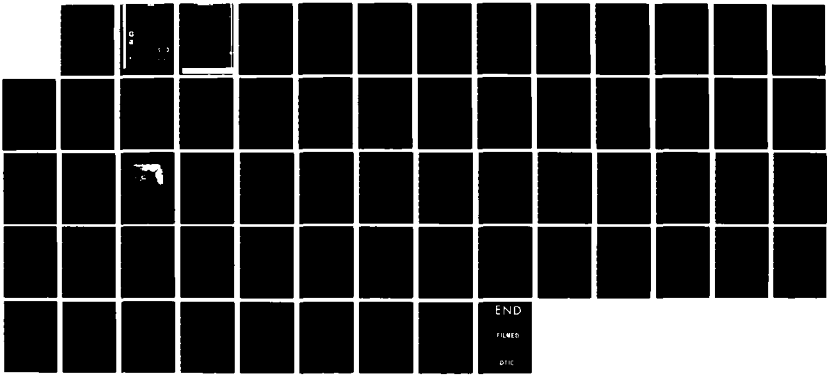

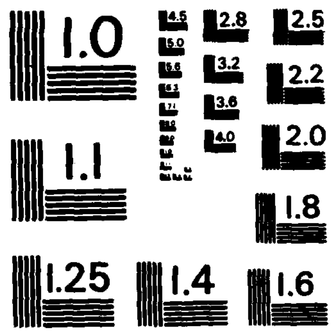
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Aviation Weather Forecasts Based on Advection: Experiments Using Modified Initial Conditions and Improved Analyses

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Previous experiments had shown that upper-level wind flows could be used to advect surface weather parameters to produce short-range (0-15 hours) forecasts. However, to achieve scores better than persistence, allowance had to be made for stationary weather patterns and also for diurnal changes in weather conditions. Two new forecast experiments were prepared and carried out, using data from 12 cases during March 1983. First, data were edited and adjusted to reduce effects of local conditions (altitude, surface roughness), and then were advected. Finally, the adjustment was removed. The forecasts using a 500 mb space-averaged flow with modified initial conditions produced improved advection forecasts, with some parameters better than persistence and MOS (Model Output Statistics) for 2-7 hours.

In the second experiment, an improved objective-analysis procedure was introduced, one based on the "Barnes" approach, which uses one-half degree (about 45 km) resolution and previous analysis as a first guess. (Prior analyses were 1 degree, single (Contd)

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pass, "Cressman"-type analyses). These improved analyses resulted in a somewhat better score for 1-3 hours (using a "change-advection" technique), but were slightly worse at longer periods. Apparently, the small-scale patterns recovered by the improved analyses were largely either short-lived or stationary. These conditions would not lead to better advection forecasts. Further examination revealed that those parameters most difficult to resolve in the objective analyses (visibility, ceiling, and wind speed) also had the lowest forecast skill scores for persistence. Suggestions for future experiments include introduction of satellite information and improved adjustment of initial data.

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1. INTRODUCTION

In spite of remarkable developments in remote sensing and data processing, little skill is displayed in forecasting weather changes over periods of 1 to 12 hours for aviation terminals.[1] The numerical prediction models now do a commendable job forecasting changes in the large-scale weather patterns over periods of 12-48 hours, but many problems must be overcome before these prediction models can be used operationally to make short-range forecasts of surface weather conditions. To illustrate, for any weather parameter, say Q (wind component, temperature, visibility), we can write a local forecast equation in the form

$$\frac{\partial Q}{\partial t} = -\vec{V} \cdot \nabla Q + \frac{dQ}{dt} . \tag{1}$$

local change term	advection term	nonconservative term

(Received for publication 17 January 1985)

1. Muench, H.S. (1982) An Appraisal of the Short-Range Forecast Problem Using Power Spectra, AFGL-TR-82-0353, AD A129315.

At levels above the boundary layer (1.5 km to 20 km), the equations for wind, temperature, and humidity are fairly easy to solve, as the nonconservative term is either vanishingly small or can be expressed in terms of other variables. However, aviation terminals are located at the bottom of the boundary layer, where the nonconservative terms can be very important. These terms include surface fluxes of momentum, heat, and water vapor. In addition, over a period of a few hours, the hydrometeors that make up clouds, precipitation, and visibility restrictions are constantly settling out and being replaced through nonconservative processes. Thus, the physics of short-range forecasting of surface weather conditions is quite complex, and forecasting is a very difficult task.

One approach to the problem is to assume that the nonconservative term is related to atmospheric dynamics that are propagating systematically, as if advected. For example, the clouds may be formed by vertical motions related to moving synoptic-scale patterns, and the visibility reduction may be related to a moving pattern of precipitation falling into the boundary layer. Thus, we can write

$$\frac{\partial Q}{\partial t} = -\vec{V}^* \cdot \nabla Q \qquad (2)$$

where V^* is the wind field advecting the weather patterns.

This equation can be easily solved (graphically or by computer) to produce local forecasts with high temporal resolution once $\vec{V}^*$ is known. The forecast procedure is to simply step upstream at, say, hourly intervals, with distances proportional to speed, and, at each point, extract the corresponding value of Q, which is advected downstream to become the forecast. The technique can take full advantage of the airways observations, which have a spacing of about 60-120 km in the eastern United States, thus resolving disturbances with equivalent wave lengths of about 300 km. By contrast, the Limited Area Fine Mesh* (LFM) model uses data with 300-400 km spacing and analyzes disturbances down to about 1000-km wavelength (though somewhat smaller scales may be generated in forecasts).

To make a forecast, one does need the field of $\vec{V}^*$. One way to determine this vector is to use two (or more) recent charts of Q, separated in time, and determine the motion vector which best explains the changes in the patterns. Muench[2] noted that this approach can objectively produce forecasts of cloud

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*The LFM is the current operational prediction model of the National Weather Service used for local forecasts.

2. Muench, H. S. (1983) Short-Range Forecasting of Cloudiness and Precipitation Through Extrapolation of GOES Imagery, AFGL-TR-81-0218, AD A108678.

amount and precipitation probability better than persistence for periods of 2-7 hours (using satellite imagery). In addition, forecasts using the 700-mb wind instead of the motion vector based on recent change in pattern were very nearly as accurate and, of course, simpler to obtain. This latter result was not surprising; forecasters for the past 30 years or more have used 700-mb (3 km) winds to predict motion of precipitation patterns as one of many subjective "rules of thumb."

The advection technique has the potential for providing useful short-range forecasts without a formal solution of the dynamic equations in a mesoscale environment. To evaluate this potential, we made a series of developments and tests with successively increasing complexity. First was a rather simple test (Experiment 1) that uncovered some basic problems. Then, in Experiments II and IIIA, we made and tested modifications to the advection technique that compensated for stationary patterns and diurnal changes. With Experiments IIIB and IIIC, we made improvements by including editing and pre-processing of data (IIIB) and by introducing higher-resolution objective analyses (IIIC). This report will first review results of experiments I, II, and IIIA (previously published[1, 2, 3, 4]) and then describe the developments and testing for Experiments IIIB and IIIC. Finally, a discussion of inherent difficulties in short-range forecasting and suggestions for future research are included.

2. REVIEW OF EXPERIMENTS I, II, AND IIIA

The first step was to conduct Experiment I, a forecast experiment using upper level winds to make short-range forecasts of surface weather parameters using the concept of simple advection. For this test, and for subsequent tests, forecast errors were evaluated by comparison of root-mean-square (rms) errors with errors for persistence (no change with time from current conditions). In addition, forecasts were also compared with the operational model-output-statistics (MOS) forecasts,[5] based on the local observation, and also forecast parameters from the LFM. Forecasts were made for cloud amount, surface wind,

3. Muench, H.S. (1983) Experiments in Objective Weather Forecasting Using Upper-Level Steering, AFGL-TR-83-0328, AD A143393.

4. Muench, H.S. (1984) Objective short-range weather forecasts experiments using meso-scale analyses and upper-level steering, Preprints, 10th Conference on Weather Forecasting and Analysis, Am. Meteorol. Soc. pp. 241-248.

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

visibility, and dewpoint for time periods of 0-15 hours, using the AFGL McIDAS (interactive computer system) minicomputer and display together with software written by the University of Wisconsin.

The net results of the forecast test for the single advection model were rather disappointing.[1] The forecasts for most of the parameters and most of the time periods were worse than persistence. Even when better than persistence, the advection forecasts were worse than the MOS forecasts. At this point, the following sources of potential errors and possible solutions were examined:

A. The analyzed field of Q contains both stationary and moving disturbances, and serious errors result when the quasi-stationary patterns are advected.

B. The nonconservative term contains effects of the diurnal heating and cooling of the boundary layer. This has the effect of a disturbance moving westward at 15 degrees of longitude an hour, totally unrelated to the 700-mb flow. Diurnal boundary layer changes have the greatest effect on temperature, but visibility, ceiling and wind speed are also affected.

C. Because of McIDAS computer limitations, the weather parameter analyses used in the forecast were done on a 1-degree latitude-longitude grid with a single pass Cressman-type routine,[6] which tends to oversmooth in data-rich areas.[7] Some small disturbances were probably lost in the objective analysis and not forecast.

D. A single advection flow based on analyzed wind fields may not be best for all parameters. In particular, flows nearer the surface might be better for visibility and dewpoint. Unfortunately, the low-level flows can change rapidly with time, particularly with passage of cyclones and anticyclones.

In all likelihood, factors A through D contributed to the poor performance of the simple advection technique. Thus, we made an increasingly complex series of technique modifications. With each modification, a specific factor was addressed, the forecast procedure was changed, and a forecast experiment conducted.

The first problem to be considered was the effects of stationary patterns, related to orography. If the stationary patterns are advected, forecast errors will result. One solution is to forecast observed changes in Q rather than the value itself. The changes are advected and then added to the initial condition to produce a forecast, a procedure we call "change-advection."

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6. Cressman, G. P. (1959) An operational objective analysis system, Mon. Wea. Rev. 87:367-371.

7. Gerlach, A. M. (ed.)(1982) Objective Analysis and Prediction Techniques, AFGL-TR-0394, AD A131465, Contract F 19628-82-C-0023, Systems and Applied Sciences Corp. (SASC), pp. 65-73.

Change-advection was tested in Experiment II. For 12 active weather cases during the winter of 1982-83, the change-advection technique produced forecasts better than both persistence and simple advection out to 3 hours, for wind, cloud amount, and temperature.[3] However, the forecast scores deteriorated rapidly beyond 4 hours. In the case of temperature (and, to a lesser extent, wind), the change-advection technique advected both the diurnal changes and non-diurnal changes observed between 1200 and 1500 UT and between 0000 and 0300 UT, and continued the trends out to 15 hours. When the diurnal curves flattened and reversed direction (usually at about 2100 UT and 1100 UT), large errors were incurred by the change-advection technique.

If the contribution of the diurnal cycle can be specified, it is possible to remove the effect from the initial data, proceed with the simple advection (or change advection), and then add back the diurnal component for the forecast time. A "diurnal modification" routine was developed based on this idea and was tested on a series of 12 cases in March 1983 (nominally selected at 36-hour intervals). In this experiment, Experiment IIIA, forecasts were with simple advection and change-advection, both with and without the diurnal modification. The forecasts with the diurnal modification markedly improved the forecasts of temperature and visibility. Visibility was better than both MOS and persistence at 3-9 hours.

While different versions of the advection forecast techniques were tested, upper-level flows other than the 700-mb wind were also tested. First, a vertically integrated 850-300 mb flow proved to be slightly worse than just the 700 mb flow. However, a spatially averaged and vertically integrated 700-500-mb flow produced forecasts with errors up to 20 percent smaller than the 700-mb flow, particularly for visibility, temperature, and dewpoint. The space-average was introduced when we found that the 700-mb flow was not properly predicting the eastward motion of major frontal systems.

An overall result of these enhancements to the advection technique is that each step seems to add a small improvement to the skill scores. Since there were still more steps to be taken, we were optimistic that routine forecasts based on advection might prove to be better than both persistence and MOS for 1-9 hours, for many weather elements. Thus, the project continued, first developing data editing and adjustment procedures and then introducing higher resolution objective analysis.

3. EDITING AND ADJUSTING INITIAL DATA

The procedure for archiving the hourly observations using the AFGL McIDAS consists of identifying messages received on the FAA 604 communication line, decoding the messages, packing data on disk, and periodically dumping to magnetic tape. At no point in the process is any editing performed; all data are accepted at face value.

Errors may creep into the process at any stage from the initial observation to the final archive (and subsequent recovery). Even though observers often detect their own errors and then transmit corrected reports, the McIDAS software currently is not capable of interpreting the corrections unless a complete observation including the corrected variable is transmitted. The occasional "noise" on the communication line is an additional source of error. The initial verification of the March 1983 forecasts of persistence showed a few "spikes" in otherwise smooth curves of error-versus-time plots, and further probing revealed that some serious errors were present in the verification reports, about one error for every 600 correct values. The objective analyses use about 400 reports for each variable, so it was likely that some analyses contained contamination from errors. Such contamination would lead to forecast errors if the data errors were upstream from a forecast site. Fortunately, the errors were infrequent and were to some extent reduced by the smoothing in the analysis procedure. However, it would be preferable to remove the most obvious errors before the analysis, forecasting, and verification take place.

An inspection by eye of the many thousands of numbers that go into a forecast experiment would be extremely tedious, and for such a task, computer assistance is desirable. The simplest way to detect meteorological errors is to examine either a time series or a spatial distribution of a particular variable; large errors appear as conspicuous maxima or minima. Since the observations are usually regularly spaced in time (hourly) but not in space, it is easier to set up a computer procedure if time series are used. Numerically, the sharp maxima and minima, when computed from finite differences, result in large absolute values of the second derivative. With three consecutive values, Q_1, Q_2, and Q_3, the second derivative $|(Q_1 + Q_3 - 2Q_2)|$ is computed and compared to some threshold, and action is taken when the threshold is exceeded.

A procedure to detect large errors in the March 1983 data set was developed, using a computer to scan, station by station, in an interactive mode. This allows the forecaster to decide whether to accept a suspicious value, insert a temporal interpolation, or insert a missing value. The thresholds used were 23 m/s (45 knots) for the vector wind and 20 C for temperature and dewpoint. No inspection was made for cloud cover and visibility errors, as their natural variability is great enough to cause difficulties with so simple a routine.

Besides the data errors, incompatibilities exist between observations that can cause problems for advection forecasts. For example, in the experiments using the March 1983 data base, the skill scores for wind speed were much lower than the scores for the vector wind. In effect, wind direction was better forecast than wind speed. Part of the problem is that anemometers are located at different heights above ground, and the terrain varies in roughness from site to site, so that different wind speeds could well be reported from stations with basically the same boundary layer wind.[8]

We set up a simple normalization procedure to reduce the local effects on wind speed. First, the average midday wind speed for March 1983 was computed for all stations from 30N to 50N and 65W to 95W. Then the average 850-mb wind speed was computed for the same area, using both 0000 UT and 1200 UT soundings. The overall pattern for mean wind speed for surface and 850 mb were quite similar, though the surface winds had about half the speed. A "representative" mean surface wind speed was thus assumed to be 0.50 times the monthly mean 850-mb wind speed at that site. If S is the mean surface wind speed and S_8 the mean 850-mb wind speed, a normalization factor C_s was defined by the relation

$$C_s = 0.50 \frac{\overline{S_8}}{S} \qquad (3)$$

and computed for each station. In general, major airport sites were found to have factors of about 0.8. Military airports with anemometer height of 13 feet rather than FAA standard of 20 feet had factors of about 1.2. Stations in hilly or wooded terrain also had factors of about 1.2. Some earlier computations of C_s (unpublished) had been made, based first on climatological data and then on special cases with homogeneous wind flow, and the values found were quite close to those found here. For the March 1983 data base, the arithmetic mean factor of all stations was 1.08, implying that a value of 0.46 would have been more appropriate in computing C_s rather than the 0.50 that was actually used. The standard deviation of C_s was ± 0.23, indicating that more than one third of the stations require an adjustment of 20 percent or more to the wind speed. To use this wind speed normalization, one simply multiplies each observed wind speed by C_s, makes an advection forecast, and then divides by C_s for the forecast site. This is, of course, an overall adjustment factor, and includes effects of anemometer height, micrometeorological terrain effects, and systematic effects such as elevation above sea level.

Observations of temperature and dewpoint also suffer from local effects, particularly resulting from station elevation. In principle, the change-advection

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8. Fujita, T.T., and Wakimoto, R. (1982) Effects of miso- and meso-scale obstructions on the PAM winds obtained during project NIMROD, J. Appl. Meteorol. 21:840-858.

technique can bypass this problem, but, unfortunately, the technique has not proved effective beyond 3 hours. To aid the regular advection forecasts, procedures were developed to make local adjustments to the temperatures and dewpoints. As with the wind speed, a representative monthly mean temperature was presumed to be directly related to the monthly mean 850-mb temperature. In developing algorithms for the diurnal temperature cycle, we found 1000 local sun-time temperature close to the 24-hour average. Thus, 1000 local sun-time temperatures were computed at each station ($\overline{T}$) for comparison to the mean 850-mb temperature ($\overline{T}_8$). Looking at stations within 300 meters of sea-level, the temperature pattern closely followed that of 850 mb, but with more north-south amplitude, implying greater static stability to the north. A good estimate of the sea-level monthly mean temperature $\overline{T}_E$ was found to be

$$\overline{T}_E = \overline{T}_8 + 3.9 + 5.0\{\text{Tanh}\,[(44 - \text{Lat.})/9]\}. \tag{4}$$

Local adjustments to the temperature were computed for each station by subtracting the observed mean temperature $\overline{T}$ from $\overline{T}_E$. The mean adjustment for all stations was found to be +1.58 C with a standard deviation of ±2.08 C. As with the wind factor, the temperature adjustments are to be added to the observations before the analyses and advection forecasts made, and later substracted from the forecasts, before verification.

When the monthly mean dewpoints ($\overline{H}$) were compared to the 850-mb monthly mean dewpoints ($\overline{H}_8$), the patterns in the eastern United States appeared to be poorly related, and the 850-mb dewpoint did not look suitable to compute a representative value. Instead, it was noted that the pattern of surface dewpoint was similar to the near-sea-level temperature pattern but with less amplitude, indicating the dewpoint spread was largest where temperatures were highest, with about a linear decrease towards lower temperatures (for 30N to 50N). Thus a representative dewpoint $\overline{H}_E$ was found to be

$$\overline{H}_E = .75\,\overline{T}_E - 1.36. \tag{5}$$

As with temperature, local adjustment factors for the dewpoint were computed for each station by subtracting the monthly mean dewpoints H from the calculated values of $\overline{H}_E$. For all stations combined, the mean adjustment was -1.48 C, suggesting that a smaller constant value might be more reasonable in computing $\overline{H}_E$. The standard deviation of the adjustment was ±2.48 C, actually a little larger than for temperature.

Undoubtedly, modification procedures should also be developed for other parameters such as cloud amount, ceiling, and visibility. Unfortunately, these parameters are difficult to work with because their frequencies are far from "normal." Furthermore, no obvious way exists to easily specify representative climatological estimates for comparison with observed data to develop local adjustments. With ceiling and visibility, many years of data for a given month would be necessary to obtain valid adjustments for the infrequent but operationally important low values. We left this for later study.

In Experiment IIIA, when the diurnal modification was introduced, a 2-hour time average of the analyzed surface wind components was performed before the forecasts, using McIDAS software. We felt this time average was necessary since the nominal 1- to 2-min average winds in the observations contain considerable high frequency noise that should be removed before making forecasts. For this next experiment, we introduced a running-time average as an alternative. For example, when u_1 is the current u-component and $\hat{u}_2$ is the previous running mean, then the current running mean $\hat{u}_1$ is computed by

$$\hat{u}_1 = \alpha u_1 + (1 - \alpha)\hat{u}_2 \tag{6}$$

where, based on a few experiments, a value of 0.55 was determined for α. In practice, running-time averages of each component would be computed and time-averaged direction and speed derived.

Up to this point, procedures were developed to adjust wind speed, temperature, and dewpoint for local effects, to edit observations of wind, temperature, and dewpoint, and also to use a running-time average for wind. In order to run an experiment that could be compared with the previous experiments, Experiment IIIa, archived data for March 1983 were edited, adjusted, time-averaged, and then repacked in the original form so that objective analysis could be made using the same McIDAS software.

Previous experiments had indicated a definite advantage in using space-averaged winds for advection rather than just the 700-mb winds (though not necessarily for all parameters). The 850-mb wind had been considered as a potentially useful advection flow, particularly for temperature, dewpoint, and visibility. However, we were concerned that the flow might change too rapidly with time to make valid forecasts for more than a few hours. To allow for such changes, a procedure was developed to use the space-averaged 500-mb wind to advect the 850-mb wind and then use the advected 850-mb wind to advect the surface weather parameters--a "double-advection" technique.

The last step before performing a new forecast experiment with all of the new enhancements was to make the appropriate modifications to the computer programs.

The forecast software was set up to test four different advection flows. First, a simple 700-mb advection flow was included in order to compare results with previous experiments. Next, a space-averaged 500-mb flow was constructed by averaging 16 degrees in longitude and 12 degrees in latitude. This space-averaged flow* was used as the second advection flow and also served as the first step in the double-advection procedures. The third advection flow was a double-advection procedure where the space-averaged flow advected the 700-mb flow, which then advected the weather parameters. The last advection flow was also double-advection, but using 850-mb instead of 700-mb flow.

The results of this new forecast experiment (Experiment IIIB) are shown in the form of tables of skill scores and rms errors in the Appendix. In addition, plotted values of skill score (relative to persistence) vs time are shown for six parameters in Figures 1-6. In these figures, two curves represent skill scores (relative to persistence) for simple 700-mb advection for Experiments IIIA and IIIB. A comparison of the two curves provides a basis for judging the effects of adjusting the input data. In Experiment IIIA, we noted that, for a given parameter, no single advection technique was superior at all time intervals. A forecaster would do best using different techniques for different intervals. Thus, these figures also show a "best-combination" curve, based on the best two or three advection techniques. The composition of each combination will be noted in the following paragraphs. These best-combination scores indicate potential forecast value for advection techniques when the magnitudes are greater than zero, and, of course, should be compared to the MOS scores that are also shown in the figures.

While we did not edit the cloud data and adjustment for local effects, we made a small modification to the program to prohibit forecasts of negative cloud amounts or greater than overcast. This did result in the small improvements that can be seen (Figure 1) for the 700-mb advection scores of Experiment IIIB over IIIA. The best combination consisted of change-advection for the first 2 hours and advection with diurnal modifications for 3 to 15 hours, all using the 500-mb space-averaged winds (double advection forecasts were not as good). This best combination is better than MOS and persistence at 3 hours, and slightly worse than MOS at the next point at 9 hours. The crossover point is about 7 hours. These results are certainly encouraging, especially since there are prospects of doing even better when satellite data can be included.

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*Following the graphical 500 mb forecast techniques of 1950s, 80 percent of the space-averaged flow was used. The 80-percent factor is believed to be necessary because the "level of nondivergence" is near 600 mb rather than 500 mb.

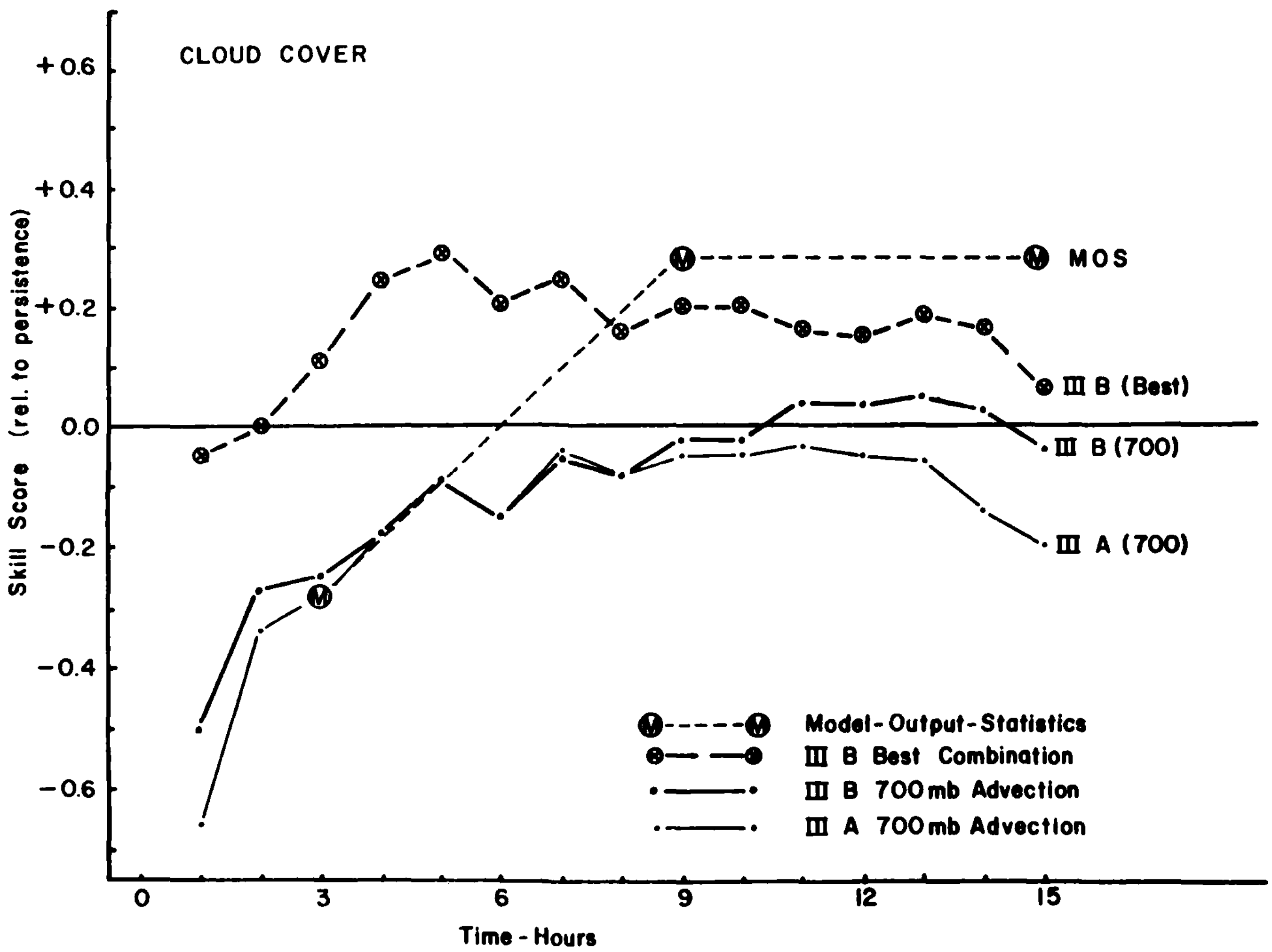

Figure 1. Forecast Skill Scores (Relative to Persistence) for Experiments IIIA and IIIB: Cloud Cover

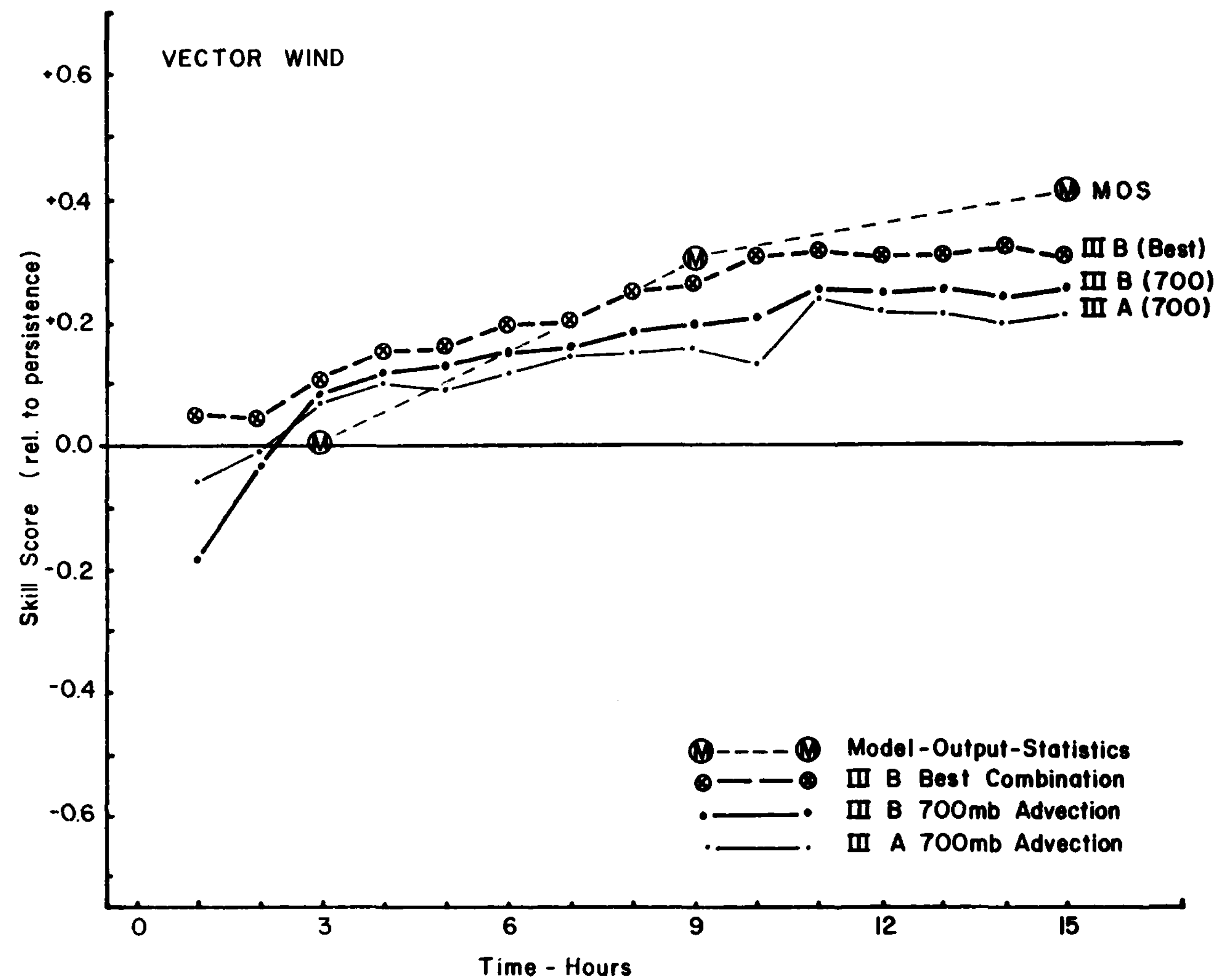

Figure 2. Forecast Skill Scores (Relative to Persistence) for Experiments IIIA and IIIB: Vector Wind

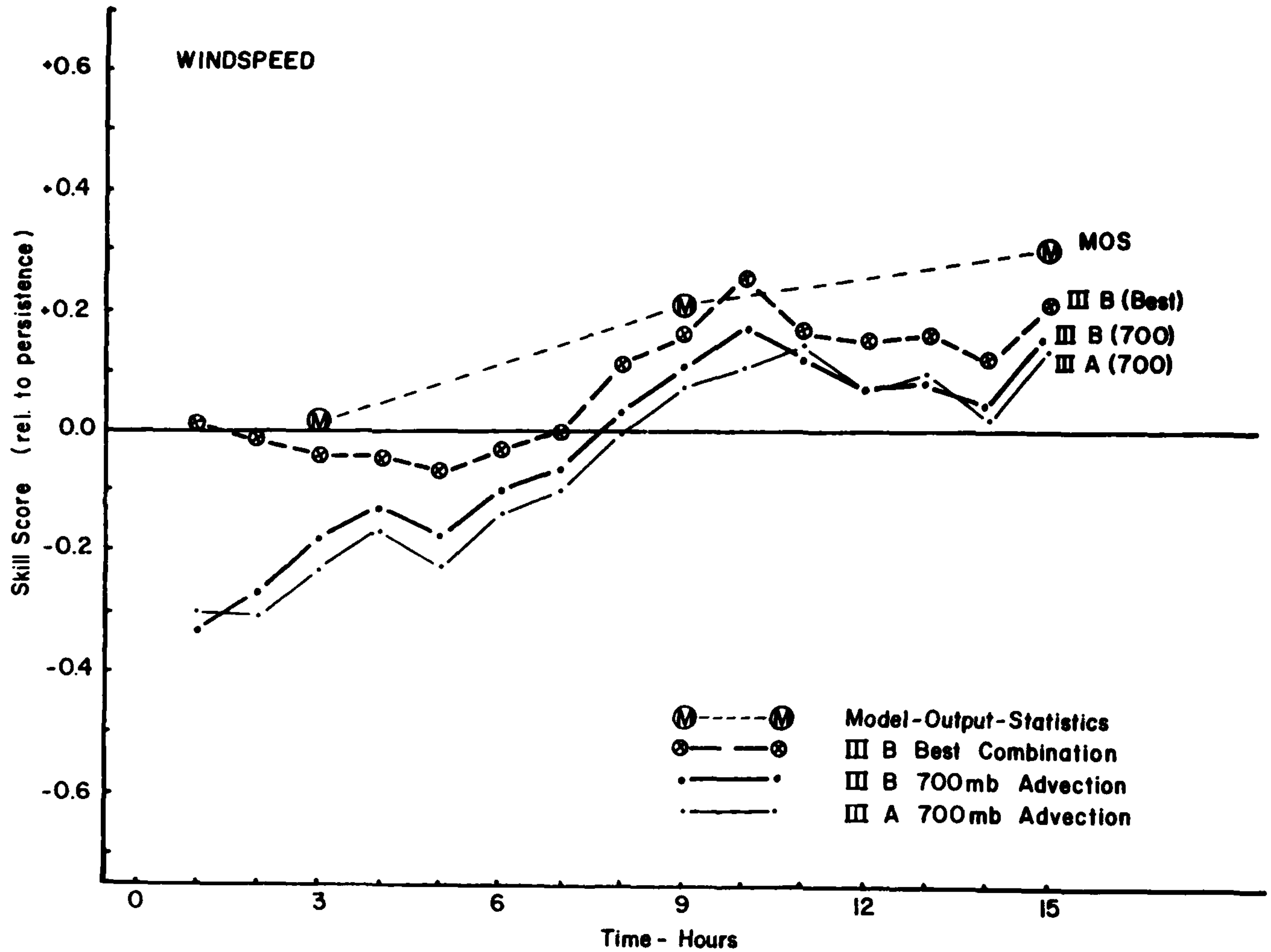

Figure 3. Forecast Skill Scores (Relative to Persistence) for Experiments IIIA and IIIB: Wind Speed

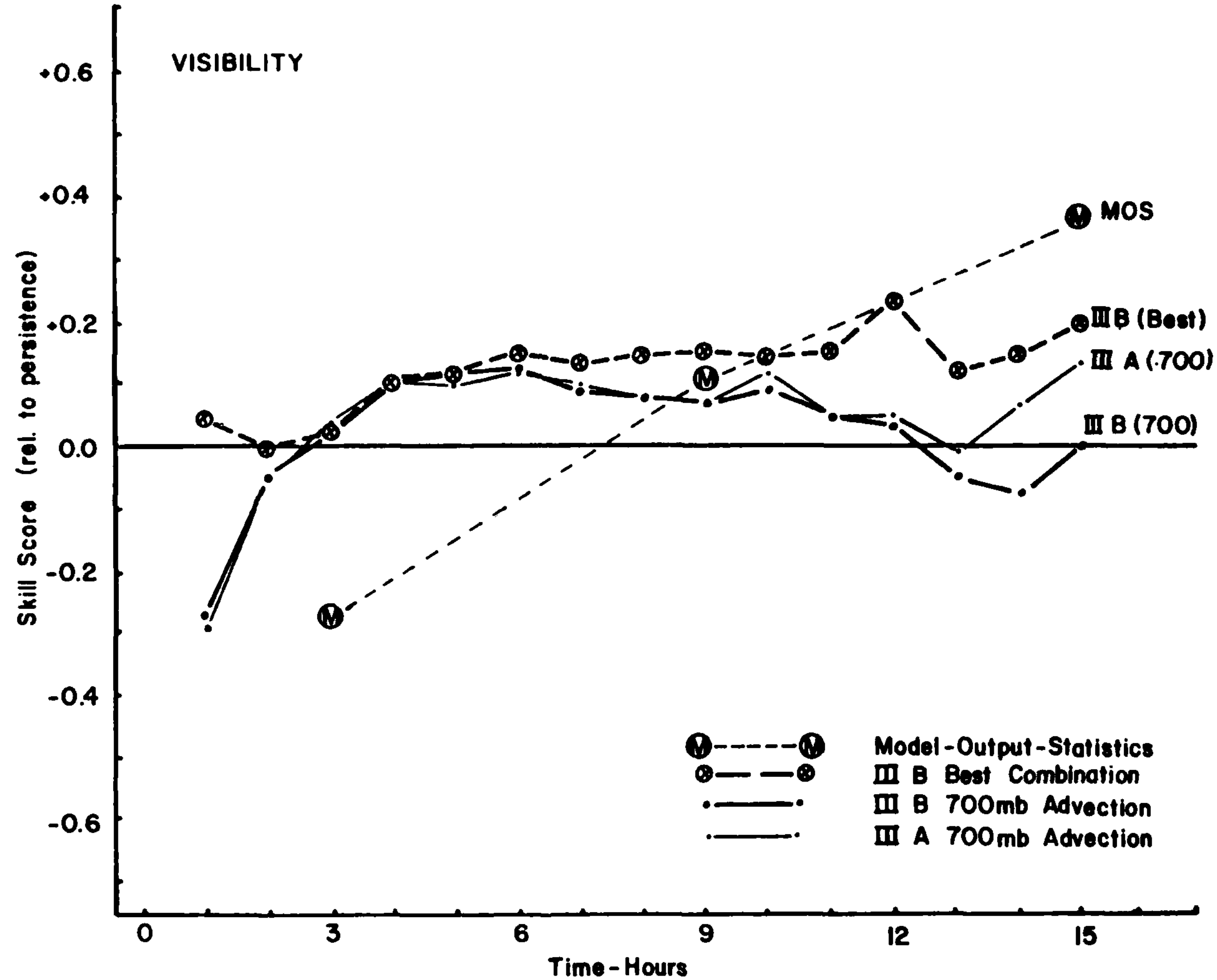

Figure 4. Forecast Skill Scores (Relative to Persistence) for Experiments IIIA and IIIB: Visibility

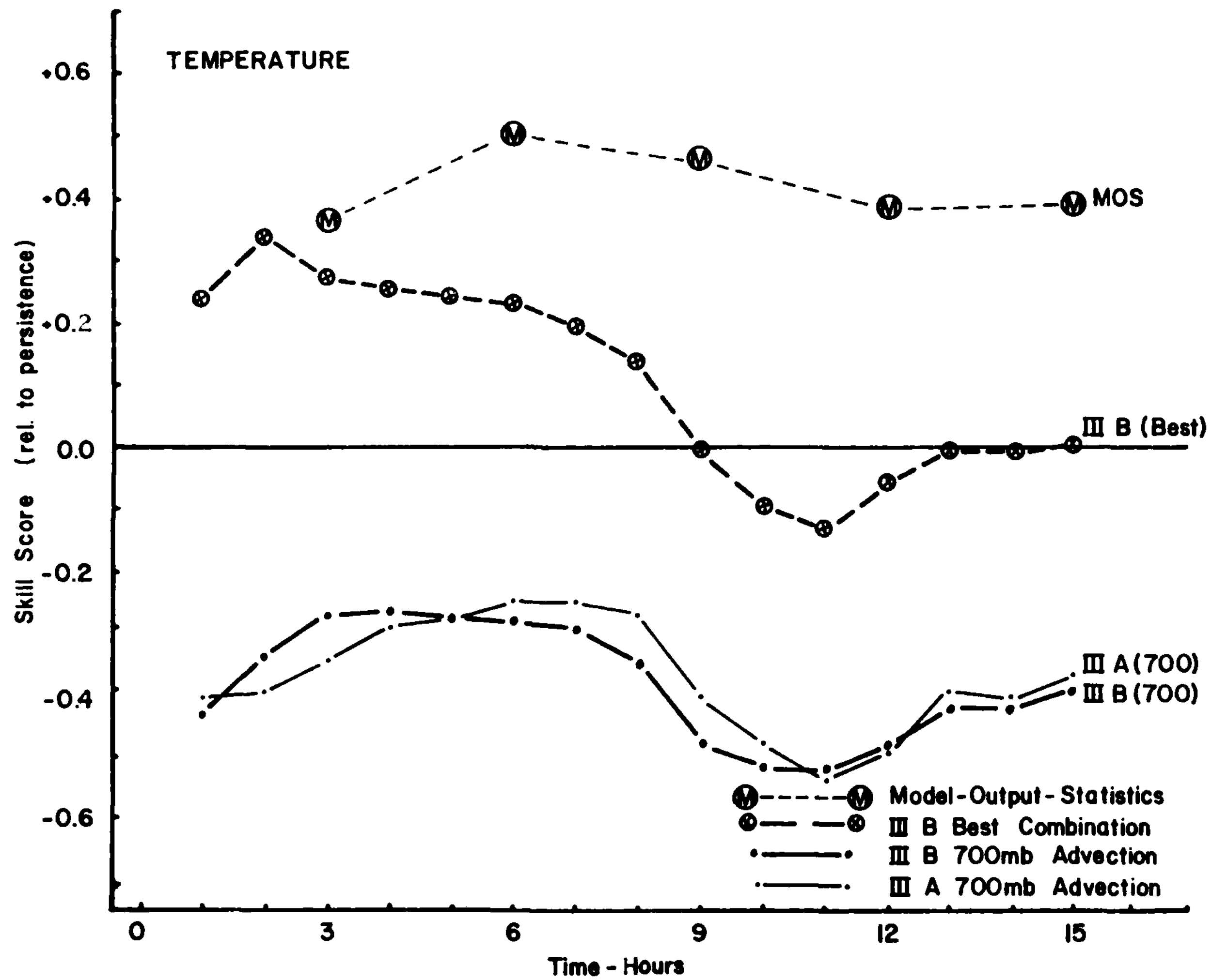

Figure 5. Forecast Skill Scores (Relative to Persistence) for Experiments IIIA and IIIB: Temperature

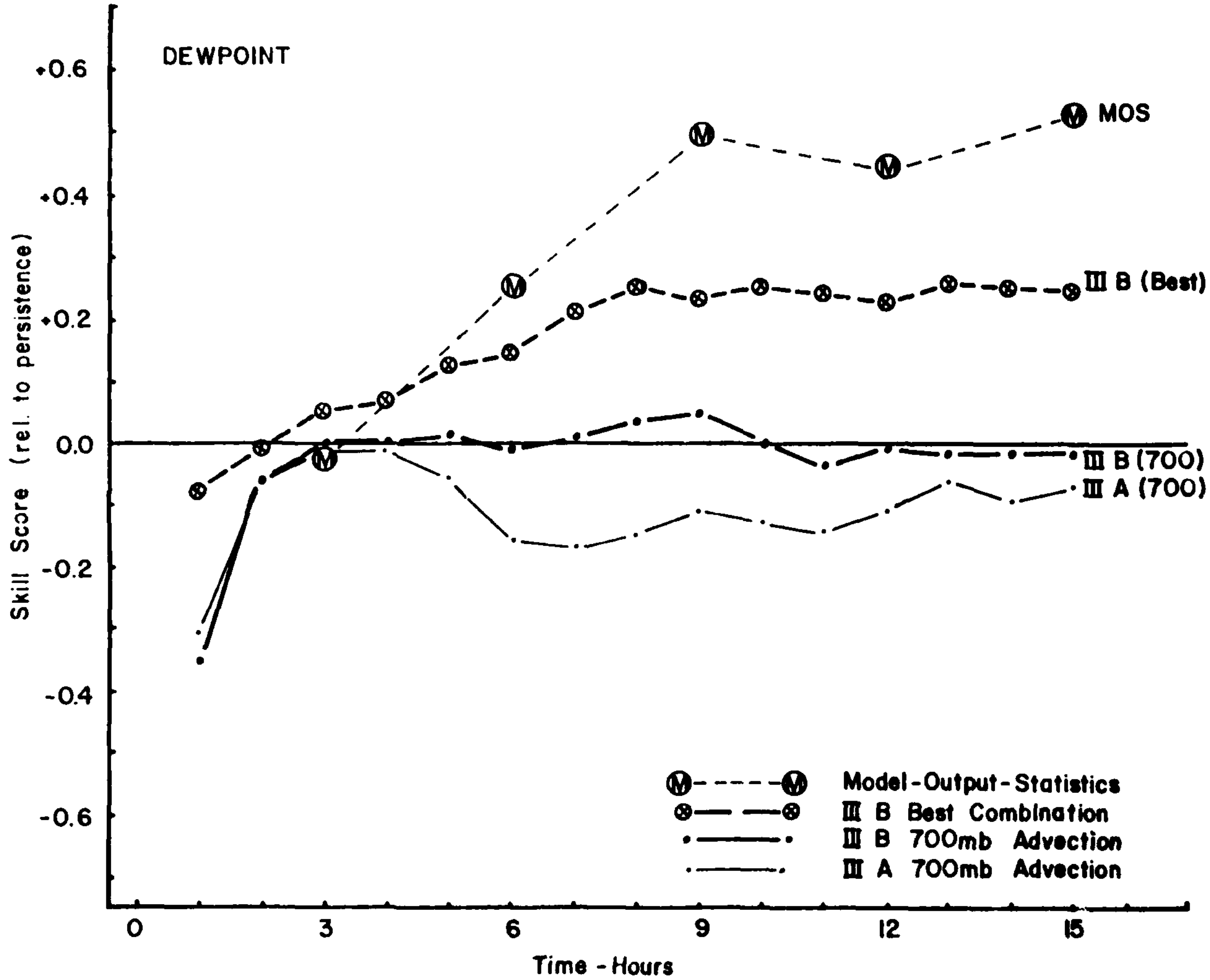

Figure 6. Forecast Skill Scores (Relative to Persistence) for Experiments IIIA and IIIB: Dew Point

Figure 2 shows that the adjustments to the wind data did produce small but consistent improvements to the 700-mb advection forecasts of the vector wind, at least at 3 hours and more. Though there may be a decrease in skill at 1 to 2 hours, perhaps due to the time averaging, the change-advection scores for these times did improve, resulting in the small positive scores as part of the best combination. Like the cloud amount, the best combination consisted of the change-advection for the first 2 hours, and then the advection with diurnal modification for the 3 to 15-hour forecasts, all using the 500-mb space-averaged winds. And, like the cloud amount skill scores, the best combination is better than MOS at 3 hours and slightly worse at 9 hours, with a crossover near 7 hours.

Looking at Figure 3, we note that there were improvements in the skill scores for wind speed, but only after 7 hours are the scores better than persistence. As might be expected, the best combination for wind speed was the same combination as for the vector wind. The best combination scores are slightly worse than the MOS scores at 3, 9, and 15 hours, so more work must be done. The best hopes for improvement are for a better diurnal adjustment (the routine used was not suitable for the frequent cloudy conditions in this experiment) and perhaps a better time-averaging. We should note that, for periods out to 6 hours, the rms change in wind speed was less than ± 2 m/s (4 knots, indicating that large changes, which might be caused by travelling disturbances, were relatively rare even during the month of March.

In Figure 4, the curves for the visibility forecast scores fall very nearly on top of one another. There was no editing of the visibility reports and no correction applied for local effects, so one would expect the scores for the 700-mb advection forecasts of Experiments IIIA and IIIB to be identical. The best-combination forecast is based on a 700-mb change-advection for 1-2 hours, 500-mb advection with diurnal modification for 3-10 hours, and $\overline{500}$-mb advection for 11-15 hours. The skill scores are better than those of MOS at 3 and 9 hours, though not 15 hours. The crossover point is near 10 hours.

Surprisingly, the efforts to adjust the temperatures for local effects (including station altitude) did not produce any overall improvements in the skill scores, as seen by comparing the 700-mb curves in Figure 5. The double-advection concept appears to be a step in the right direction, as the best combination was $\overline{500} \rightarrow$ 850-mb change advection for 1-3 hours, $\overline{500} \rightarrow$ 700-mb change-advection with diurnal modification for 4-8 hours, and $\overline{500} \rightarrow$ 850-mb advection with diurnal modification for 9-15 hours. The skill scores are still only comparable with those of MOS out to 3 hours, and considerably worse beyond. A closer examination revealed that the forecast scores for Washington, D.C., which is often downwind of higher elevation stations in West Virginia, did improve, but for stations east of the Great Lakes, the scores were worse. This result suggests some regional problems with the adjustment procedure. With the introduction of satellite data, the forecasts may be improved by using a cloud density factor to better account for the diurnal trends.

In Figure 6, comparing curves IIIA and IIIB, it is quite apparent that the editing and data adjustment did improve the dewpoint forecasts, with the 700-mb advection scores up to 0.2 better than the previous experiment. Here, the best combination was change-advection at 1 hour, $\overline{500} \rightarrow$ 850-mb advection for 2-5 hours, and $\overline{500}$-mb advection for 6-15 hours. Though the scores are now better than persistence for 3-15 hours, only at 3 hours are they better than those of MOS.

Overall, the results of Experiment IIIB using adjusted input data continued the trend from previous experiments showing small but useful increases in the skill scores. With the best combination of techniques, typically change-advection for the first few hours and simple advection for the longer periods, the skill scores have risen to the point that they are often better than both persistence and MOS out to about 6 hours. And some enhancements not yet tried could produce further improvement in the scores. In particular, we now proceed to an experiment using higher-resolution objective analyses.

4. HIGHER-RESOLUTION OBJECTIVE ANALYSES

At several points during the development of the advection technique, we were concerned that the objective analyses constructed by the McIDAS routines did not portray all the information available in the hourly reports, and that a more sophisticated analysis technique should be tried.

The conventional surface objective-analysis scheme in the AFGL McIDAS system is a simple, single-pass, nearest-neighbors approach.[7] It determines the gridpoint values by computing a weighted average of the eight observation values closest to each gridpoint while using a Cressman-type distance-weight function. The Cressman weight function[6] (w_n) has the form

$$w_n = (R^2 - d_n^2) / (R^2 + d_n^2) \tag{7}$$

where d_n is the distance between the observation n and the analysis gridpoint. R is the so-called scan radius which defines the distance from the gridpoint at which w_n has a value of 0.0. In this application, R is defined as the distance to the ninth closest observation site from each gridpoint. Thus, R will generally be different at each gridpoint in the analysis area.

The analysis that results from this McIDAS scheme has the advantages of speed and modest core requirements. It has the disadvantages that it suppresses mesoscale detail, the smallest grid resolution that can be selected is a 1-degree latitude-longitude grid, and the largest domain that can be analyzed is 500 gridpoints, (25 gridpoints east-west and 20 gridpoints north-south).

An alternative objective-analysis procedure that retains, to a greater extent, real mesoscale detail over a broader domain and with greater grid resolution was formulated for the CYBER 170/750 along the lines suggested by Koch et al[9] using the Barnes analysis technique.[10] It is a computationally simple objective procedure that uses Gaussian distance-weight functions. The Barnes weight function (w_n) has the form

$$w_n = \exp(-d_n^2 / \kappa_o) \tag{8}$$

where d_n is the distance between the observation n and the analysis gridpoint, and κ_o is a shape parameter of the low-pass filter response function. This analysis technique can achieve good agreement between observations and the analyzed fields, with just two iterations (or correction passes), through the use of a convergence factor γ (discussed later) that controls the degree of agreement.

In our application, a two-pass correction approach was used to adjust the "first guess" analysis. Typically, an individual case consisted of 7 consecutive hours of surface observations needing to be analyzed. The first-guess for the first hour of each case was assigned from the mean value of observations within the analysis area; for hours 2-7, the final analysis of the previous hour was used as the first guess for the next hour.

The first pass analysis, $g_1(i, j)$, obtained by correcting the first guess field at each gridpoint, $g_o(i, j)$, was determined from

$$g_1(i,j) = g_o(i,j) + \sum_{n=1}^{N} w_n (\phi_n - g_{o,n}) / \sum_{n=1}^{N} w_n \tag{9}$$

where ϕ_n is the observation and $g_{o,n}$ the corresponding interpolated value from the analysis at the location of the observation. A bilinear interpolation between the $g_o(i,j)$ values at the four gridpoints surrounding each observation point (n) were used to obtain $g_{o,n}$. In Eq. (8), a value of 36 was assigned to κ_o based on

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9. Koch, S.E., des Jardins, M., and Kocin, P.J. (1983) An interactive Barnes objective map analysis scheme for use with satellite and conventional data, J. Climate Appl. Meteorol. 22:1487-1503.

10. Barnes, S.L. (1973) Mesoscale objective analysis using weighted time-series observations, NOAA Tech. Memo ERL NSSL-62, National Severe Storms Laboratory, Norman, Okla. (NTIS COM-73-10781).

considerations suggested by Koch et al.[9] Two factors are considered: the spacing of conventional surface data in the eastern United States and the analysis grid resolution of 0.5-degree latitude-longitude. This results in the establishment of a cutoff scan radius (R_c) of 12 grid units which is "sufficiently large that the filter response characteristics remain virtually unaffected."[9]

The second (final) pass analysis, $g_2(i,j)$, obtained by correcting the first pass analysis at each grid point, $g_1(i,j)$, was determined from

$$g_2(i,j) = g_1(i,j) + \sum_{n=1}^{N} w_n^1 (\phi_n - g_{1,n}) / \sum_{n=1}^{N} w_n^1 \qquad (10)$$

where w_n^1 is the weight function comprising a convergence factor (γ) which can be varied to control the degree of convergence desired in the final analysis. It is computed from

$$w_n^1 = \exp(-d_n^2/\gamma\kappa_o) \qquad (11)$$

where κ_o, in our application, was set at 36. Figure 7 illustrated the effect of γ, which can be set at any value of 1.0 or less, on the shape of the weight function (w_n^1) depending on separation distance (d) in grid units.

Before we conducted the next stage of forecast experiments, we had to determine optimal values of γ for each surface observation element to be analyzed. The elements included: cloud cover, temperature, u and v wind components, visibility, and ceiling height. In addition, we had to decide whether to analyze visibility and ceiling height in natural logarithmic form or basic units because their reported values can range over three orders of magnitude within one analysis field. That variability can cause numerical instability in objective-analysis procedures.

Hourly observations for a 3-day period, from 1200 GMT 5 December 1983 through 1200 GMT 8 December 1983, were selected as a test sample. This sample comprised a period of active systems with substantial horizontal gradients and was deemed to be a robust test of the analysis technique. Figure 8, the surface weather map for 1200 GMT 6 December 1983, illustrates the general nature of surface weather during the test period. The analysis area is denoted by the heavy dashed border. It contains about 240 surface observation sites. The grid resolution was 0.5 degree latitude-longitude.

The evaluations were conducted along two lines: using root-mean-square (rms) error statistics and a subjective evaluation of mapped fields. Table 1 lists the overall rms error for the options on convergence factor (γ) and element form

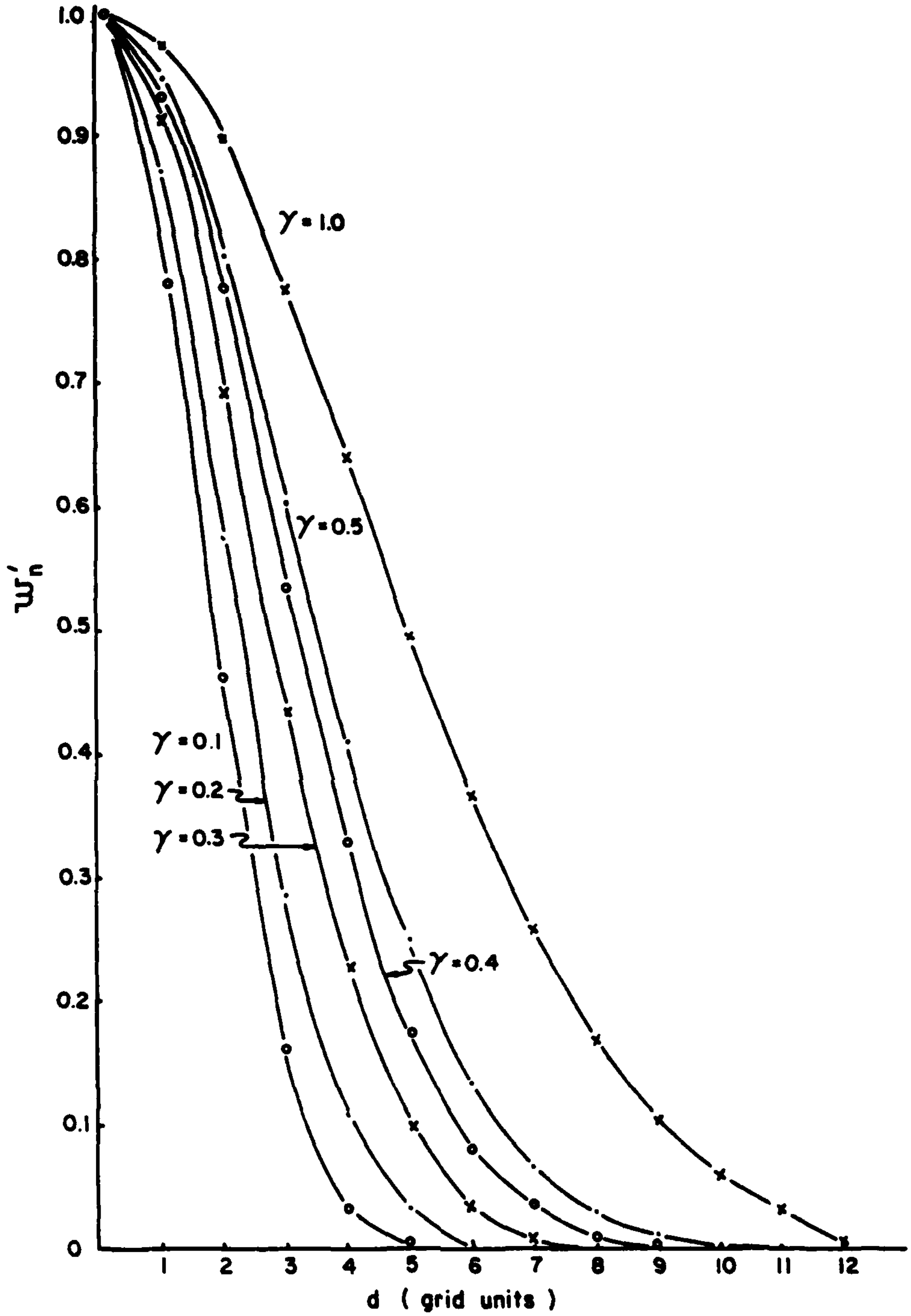

Figure 7. The Effect of the Convergence Factor (γ) on the Barnes Analysis Weight Function (w_n^1) as a Function of Separation Distance (d)

Figure 8. Surface Weather Map for 1200 UT, 6 December 1983

Table 1. Overall Error Statistics for Analysis Test Period

Element (Units)	Form	γ	RMSE
Cloud Cover (4 categories)	Basic	.3	.391
		.2	.361
		.1	.298
Temperature (C)	Basic	.4	1.159
		.3	1.076
		.2	.963
u-comp (m/sec)	Basic	.4	1.484
		.3	1.421
		.2	1.319
v-comp (m/sec	Basic	.4	1.574
		.3	1.503
		.2	1.394
Visibility (Miles)	Basic	.3	3.040
		.2	2.793
		.1	2.267
(ln mi)	Ln	.3	.547
		.2	.502
		.1	.405
Ceiling (100 ft)	Basic	.3	33.768
		.2	31.337
		.1	26.008
(ln 100 ft)	Ln	.3	.655
		.2	.600
		.1	.489

(ln vs basic) that were tested. Since we wanted to retain mesoscale detail, we restricted the variation on γ between 0.1 and 0.4.

We used all the observation locations that contributed to the analysis at each map time to develop the rms error statistics. That is, we did not withhold a certain percentage of observations from the analysis to use as independent data for verification statistics. It is not surprising then, that the convergence factors which force the greatest degree of fit or agreement between the analysis and observations yielded the lowest error statistics. For this reason, a complementary subjective assessment of the objectively analyzed maps was undertaken to examine the effect of reducing the convergence factor even lower (to 0.1 for temperature, u-component, and v-component, and to 0.05 for the sensible weather elements of cloud cover, visibility, and ceiling height).

Figures 9a, 9b and 9c show a manually analyzed visibility map (natural log) for 6 December 1983, 1500 UT, the objective analysis with γ = 0.10, and the objective analysis with γ = 0.05. The rms errors resulting from reducing the second-pass convergence factor to 0.05 for cloud cover, visibility, and ceiling

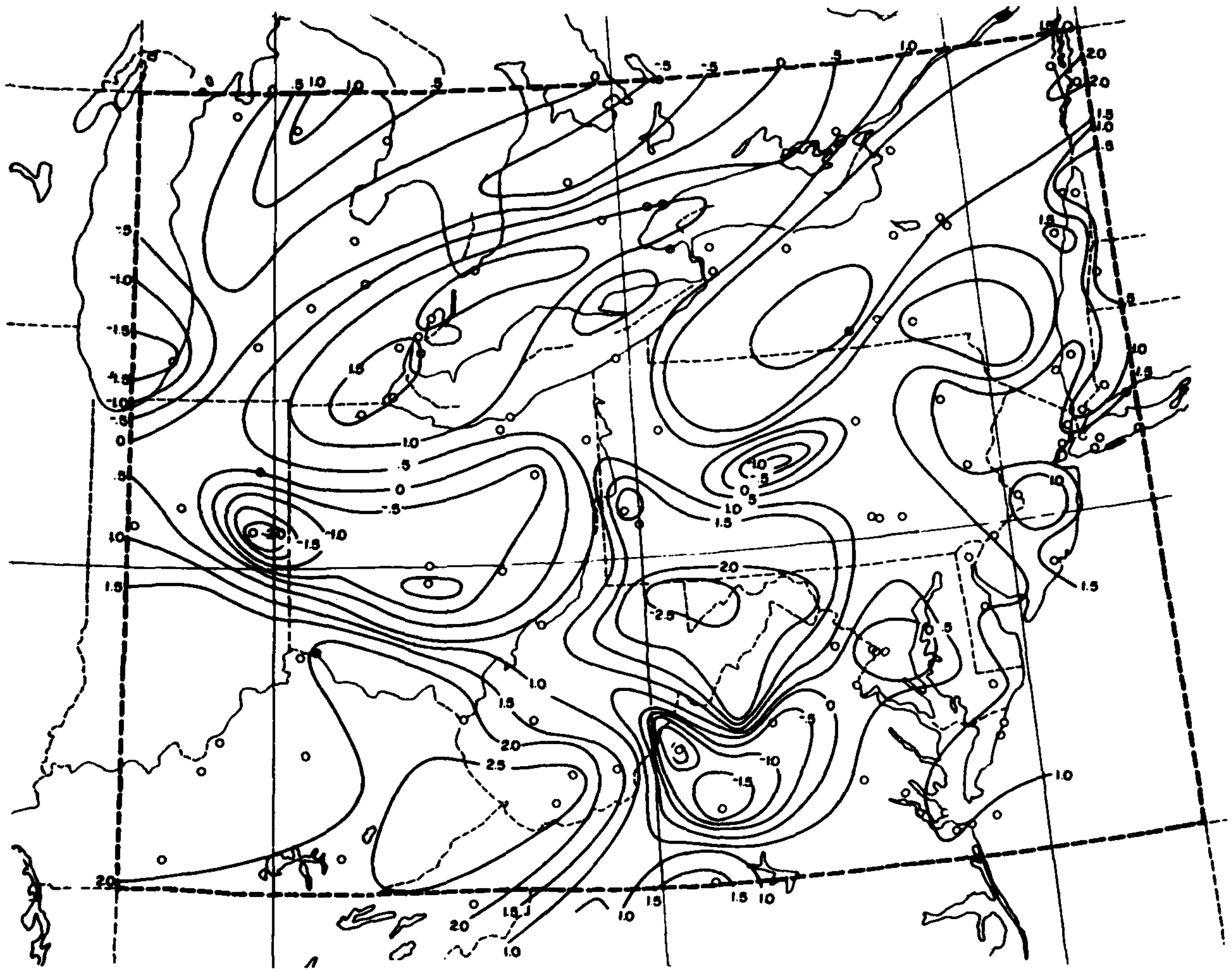

Figure 9a. Analysis of Surface Visibility (in Log Natural Form) for 1500 UT, 6 December 1983: Manual (Subjective) Analysis

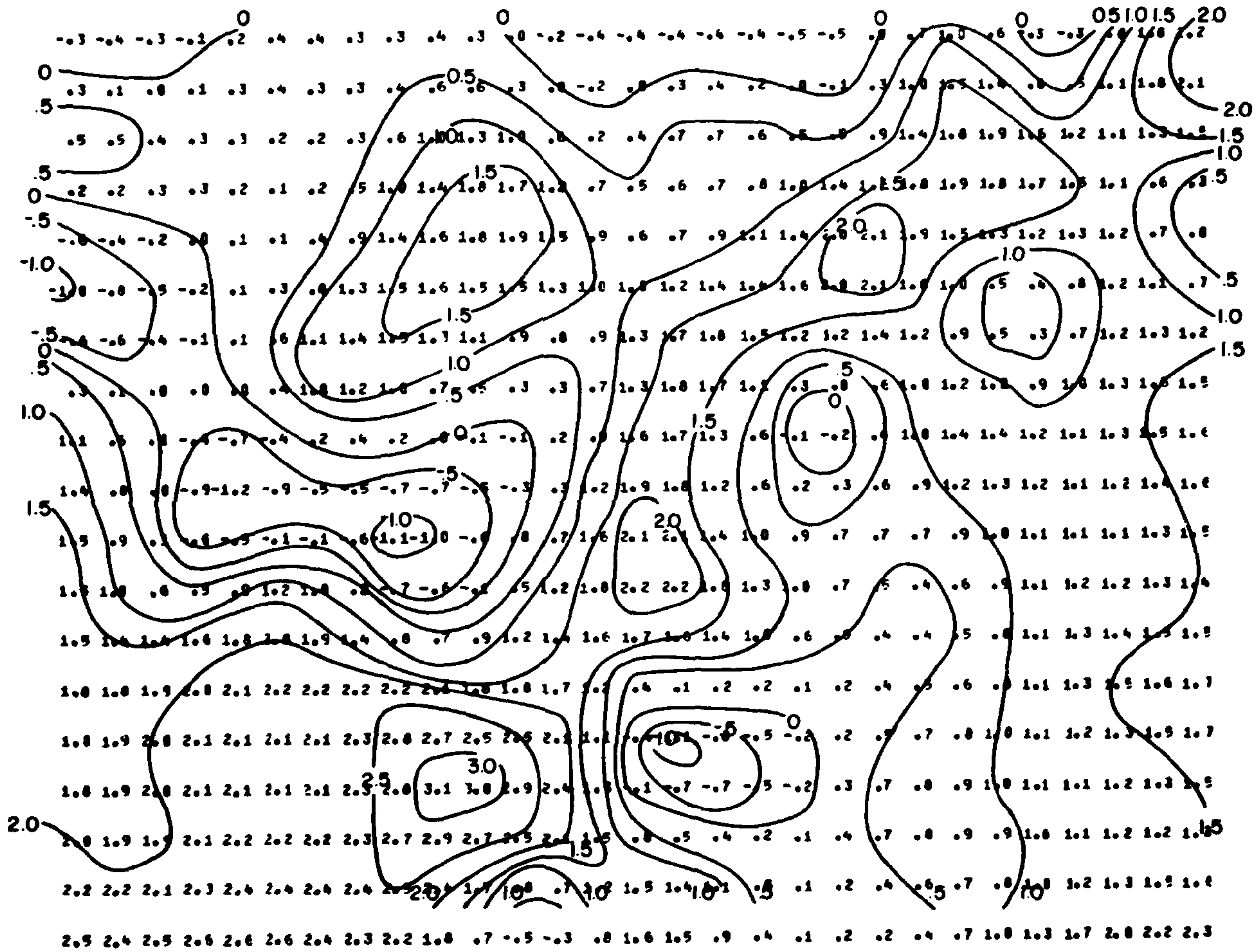

Figure 9b. Analysis of Surface Visibility (in Log Natural Form) for 1500 UT, 6 December 1983: Barnes Analysis With $\gamma = 0.10$

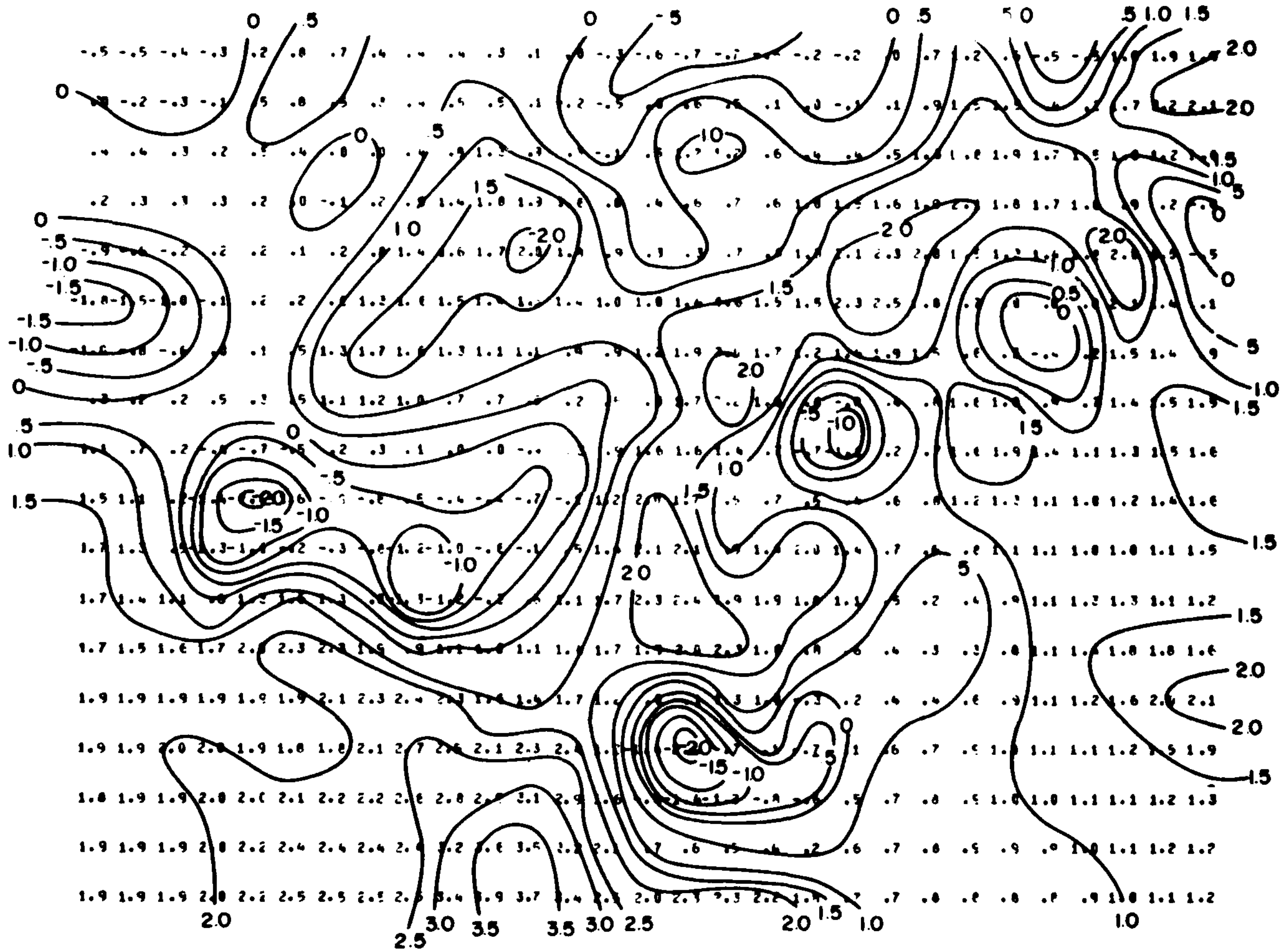

Figure 9c. Analysis of Surface Visibility (in Log Natural Form) for 1500 UT, 6 December 1983: Barnes Analysis With $\gamma = 0.10$

height, and to 0.1 for temperature and the u, v wind components were lower than for factors of 0.1 and 0.2 respectively. However, when compared (subjectively) to the manually analyzed maps, there was better agreement with maps analyzed with convergence factors of 0.1 and 0.2. For the stronger factors (0.05 and 0.1), the analyses overspecified map extrema, yielding maximum/minimum gridpoint values beyond the corresponding maximum/minimum observation values.

Experiment IIIC, the next step, tested the modified Barnes-analysis technique using the March 1983 data base and the advection forecast techniques. The primary goal for this test was to determine the improvement in forecast skill achieved by using the Barnes analysis with 0.5-degree resolution instead of the McIDAS 1-degree analyses. An improvement would be expected first because the higher resolution would mean an ability to resolve and forecast smaller disturbances than is possible with a 1-degree grid. Also, by using the previous analysis as a first guess, the time continuity is better portrayed. This should produce better change-advection forecasts than the McIDAS routine, which uses a constant first guess (usually a zero value) for each map.

In setting up Experiment IIIC, we decided to use the same McIDAS-generated upper-level wind analyses as in Experiment IIIB for the advection flow. Also, we used the same modified surface weather data. However, four changes were made in the forecast procedure. First, the cloud ceiling height was included as a forecast parameter, replacing the dewpoint temperature. Since ceiling height often varies over about three orders of magnitude, the natural logarithm was used (the thresholds for ceiling in MOS forecasts are nearly logarithmic in distribution). Unfortunately, ceiling height becomes discontinuous when the cloud cover decreases from broken to scattered, as no ceiling is defined when there is less than 0.6 cloud cover. Since total cloud cover was also a forecast parameter, a procedure was adopted where ceiling forecasts would only be verified when the sky cover was both forecast and observed to be broken or overcast. For analysis purposes, a dummy value equivalent to 45,000 ft (about 14 km) was entered for clear or scattered cloud conditions. In retrospect, a better policy might have been to enter the height of the highest scattered layer (this would be most apt to become the "ceiling" if sky cover increased). Without clouds, a condition of "missing" (which would be ignored by the analysis procedure) might have been better.

The second change concerned the way cloud amount was analyzed. In the McIDAS software, clear sky is given a value of -5, scattered cloud is 15, broken cloud is 25, overcast is 35, and precipitation is 45. The rationale was to have the zero isopleth surround the clear sky and the 30 isopleth surround the overcast sky area, but this scheme caused some difficulties in interpreting and verifying the advection forecasts. By the time Experiment IIIB was run, maximum allowed forecasts and verification was set to 35 (cloudy) and minima at -5 (clear). Note that change advection and diurnal modification could result in forecasts exceeding the limits.) For the Barnes analyses, the simpler procedure of 0 for clear, 10 for scattered, 20 for broken, and 30 for overcast was adopted.

The third change was quite minor. When the visibility is reported as 0 miles, a natural logarithm cannot be computed. In previous experiments, 0.05 mile was added to each visibility before the logarithm was computed. In Experiment IIIC, 0.05 mile was entered only when the visibility was less than 0.10 mile.

The last change also involved the visibility. In previous experiments, the McIDAS software made objective analyses of visibility, advection forecasts were made, and then (prior to verification) the forecast values (in miles) were converted to a natural logarithm. Presumedly, an objective analysis would better depict patterns of low visibility if the conversion to logarithm were made before the analysis. Thus, for Experiment IIIC, analyses and forecasts were based on the natural logarithm of reported visibility values and the natural logarithm of ceiling height.

These four changes were introduced in the advection forecast software, which also had to be modified to accept the higher resolution grids (four times as many points). Then, the 12 forecast cases for March 1983 were run, producing forecasts out to 15 hours at 12 different forecast sites. The results are shown through skill score vs time for the six forecast parameters in Figures 10-15. In addition, more detailed information is presented in Tables A1-A12.

Overall, the results are somewhat disappointing. Figures 10-15 compare scores for Experiment IIIB (thin line) with Experiment IIIC (bold line) for 700 mb advection (solid line) and best combination (dashed line). For cloud amount, the Experiment IIIC forecasts are clearly better. For the other parameters, they are, if anything, slightly worse, particularly for time periods beyond about 4 hours. To better compare Experiments IIIB and IIIC, skill scores based on 1-4 hours change-advection (500 mb) and 5-9 hour advection (500 mb) were computed and are presented in Table 2 (these approximate best combination scores). The scores are also stratified by time, with six cases (up to 72 forecasts) for 0300 UT forecasts and six cases for 1500 UT forecasts. The time breakout was made to note any difference between the day forecasts and night forecasts since about 15-20 percent more observations were available in the daytime. In this table, it is clear that the cloud amount forecasts are improved for both day and night forecasts and for both 1-4 and 5-9-hour forecasts. The scores for change advection for wind are essentially the same, but the IIIC advection scores for 5-9 hours are slightly worse, both day and night. The 1-4-hour change-advection forecasts for visibility are a little improved at night and worse by day, and the 5-9-hour advection forecasts are worse at both times. The 1-4-hour change-advection temperature forecasts are also a little

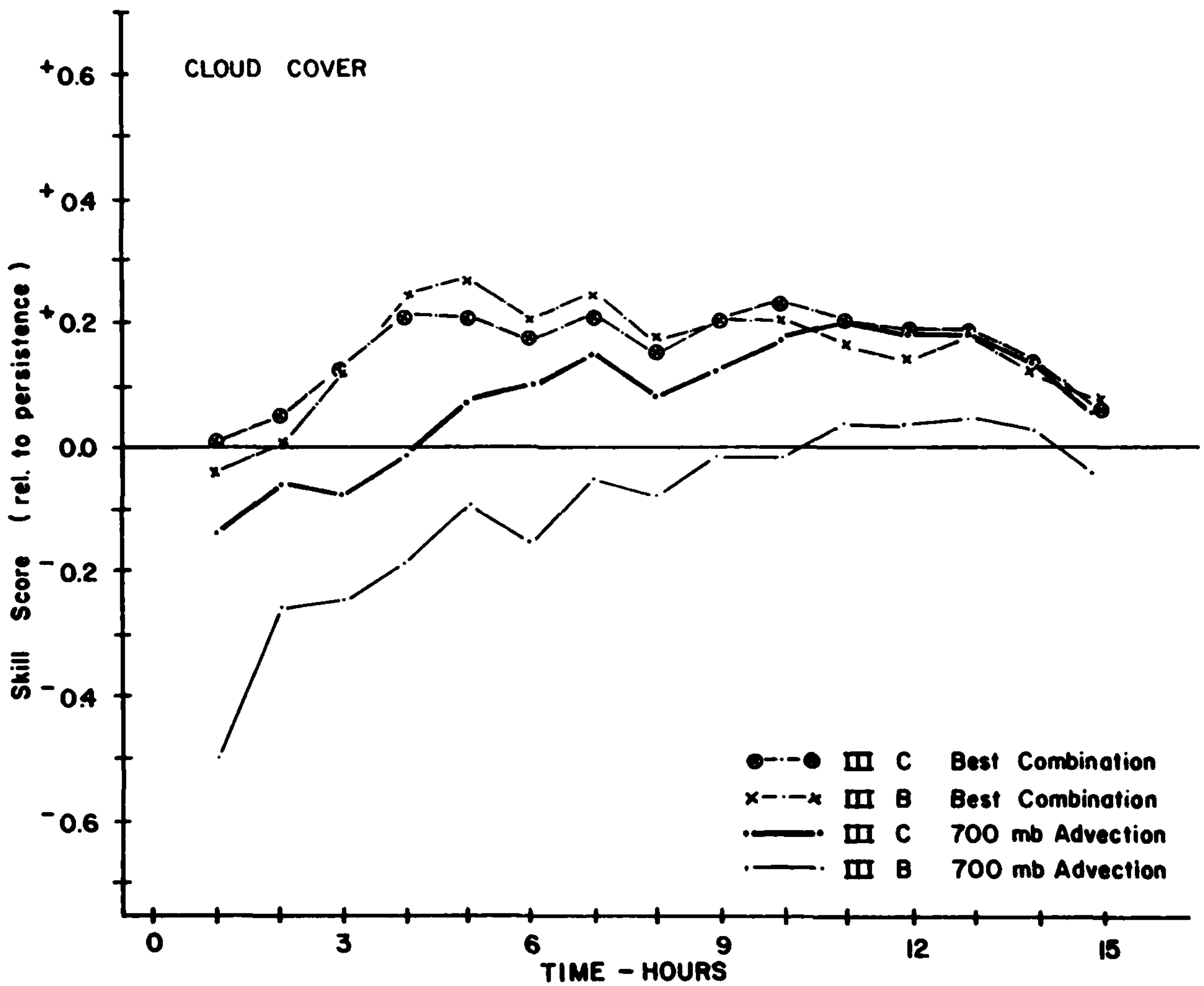

Figure 10. Forecast Skill Scores (Relative to Persistence) for Experiments IIIB and IIIC: Cloud Cover

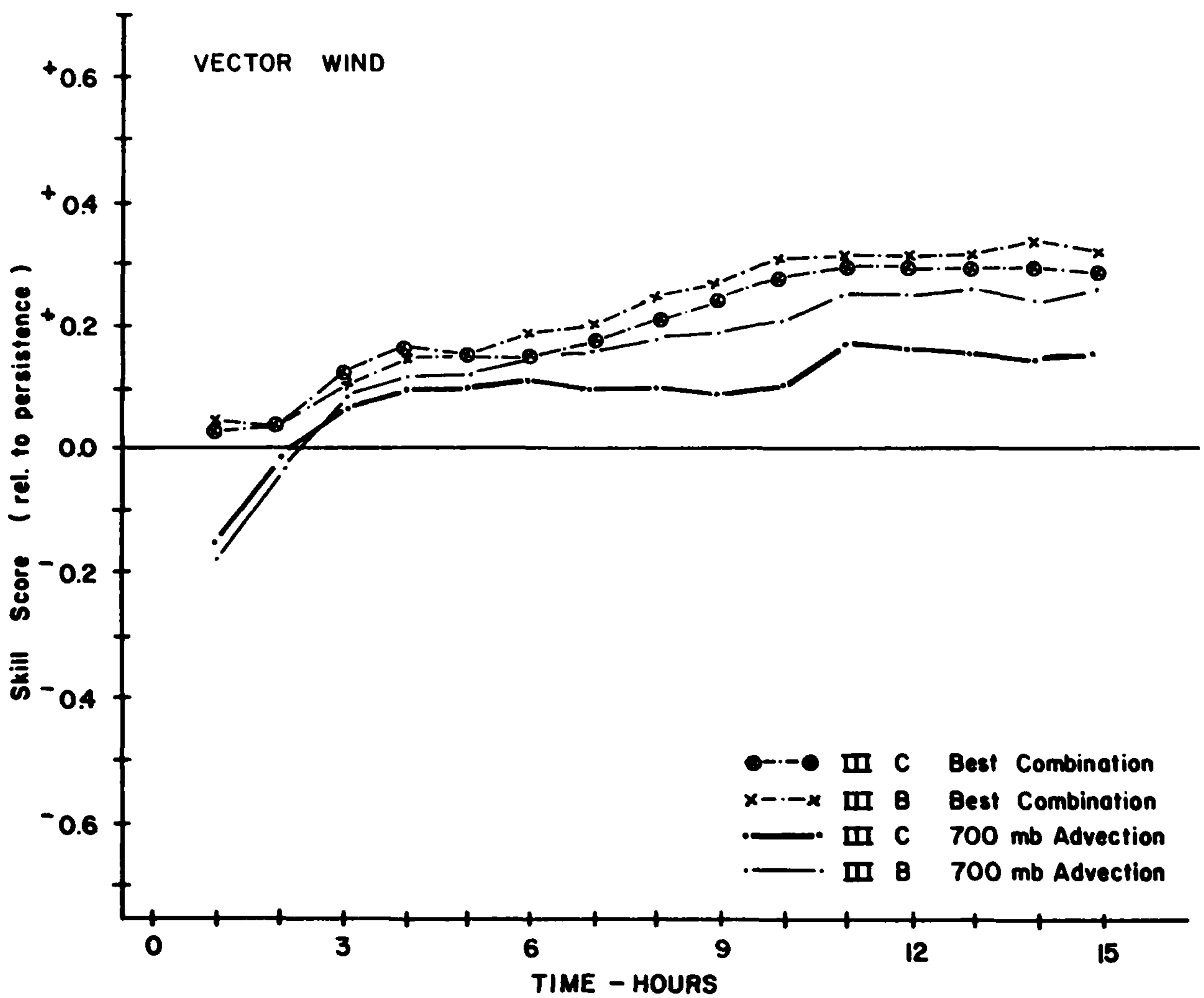

Figure 11. Forecast Skill Scores (Relative to Persistence) for Experiments IIIB and IIIC: Vector Wind

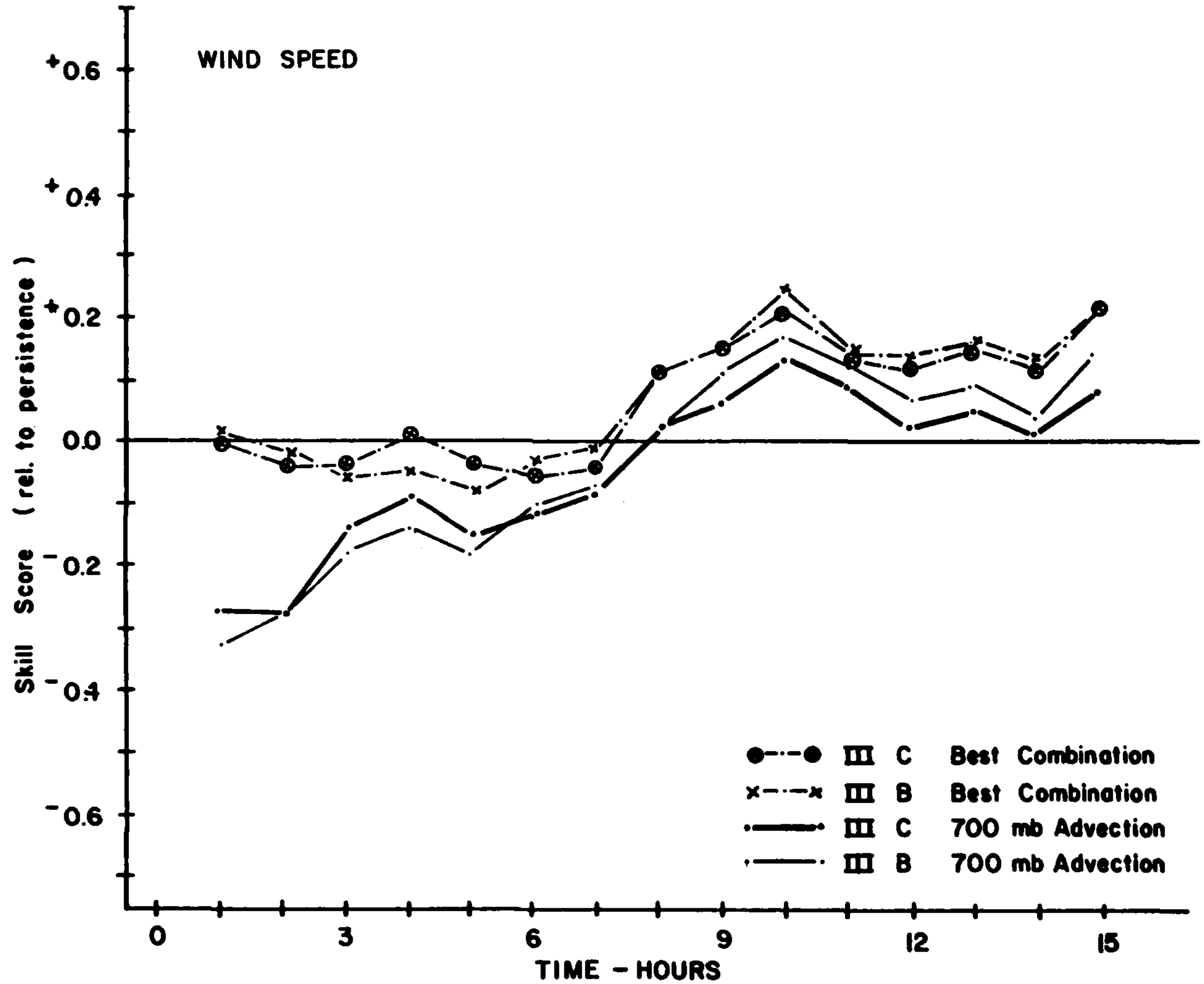

Figure 12. Forecast Skill Scores (Relative to Persistence) for Experiments IIIB and IIIC: Wind Speed

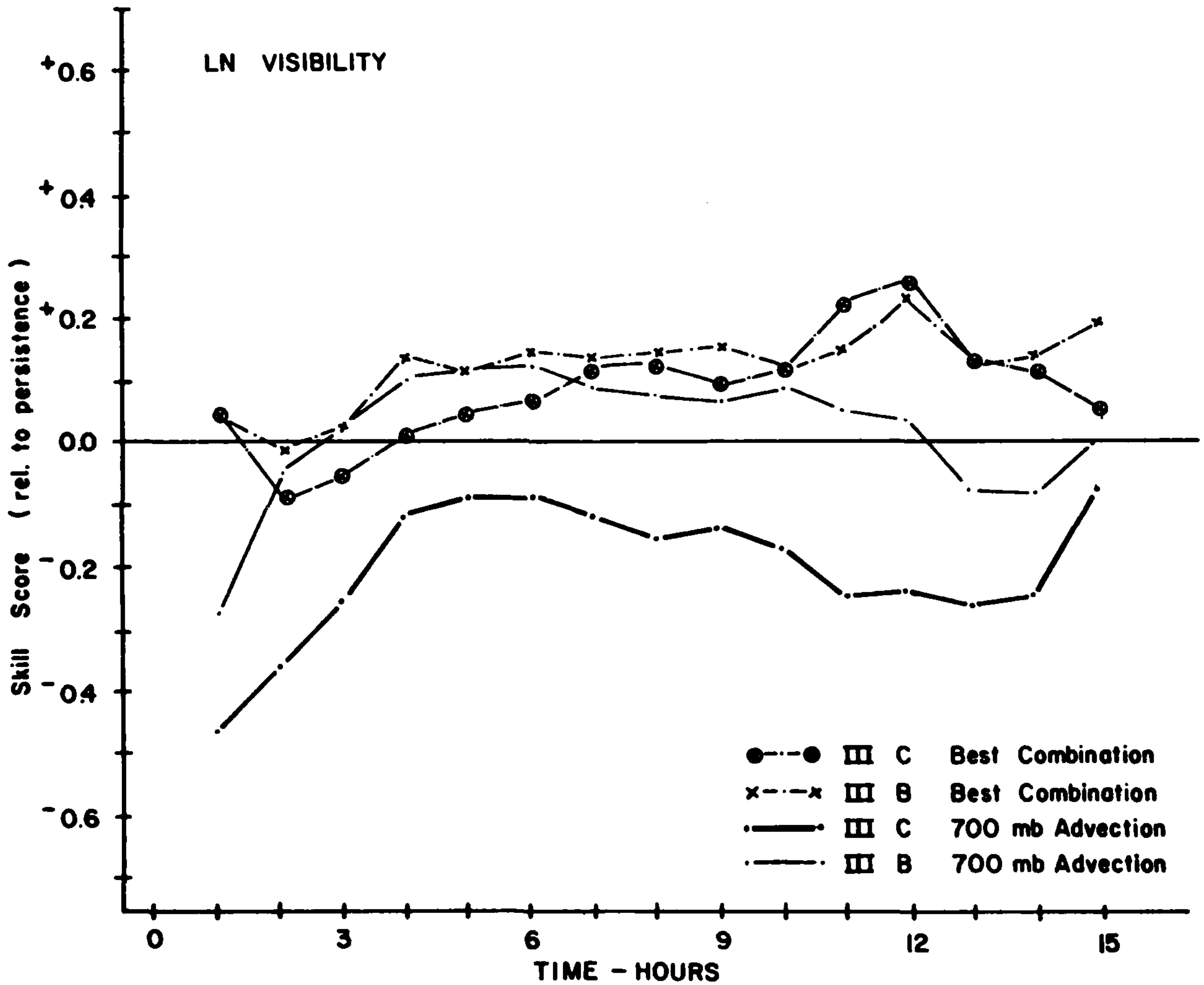

Figure 13. Forecast Skill Scores (Relative to Persistence) for Experiments IIIB and IIIC: Visibility

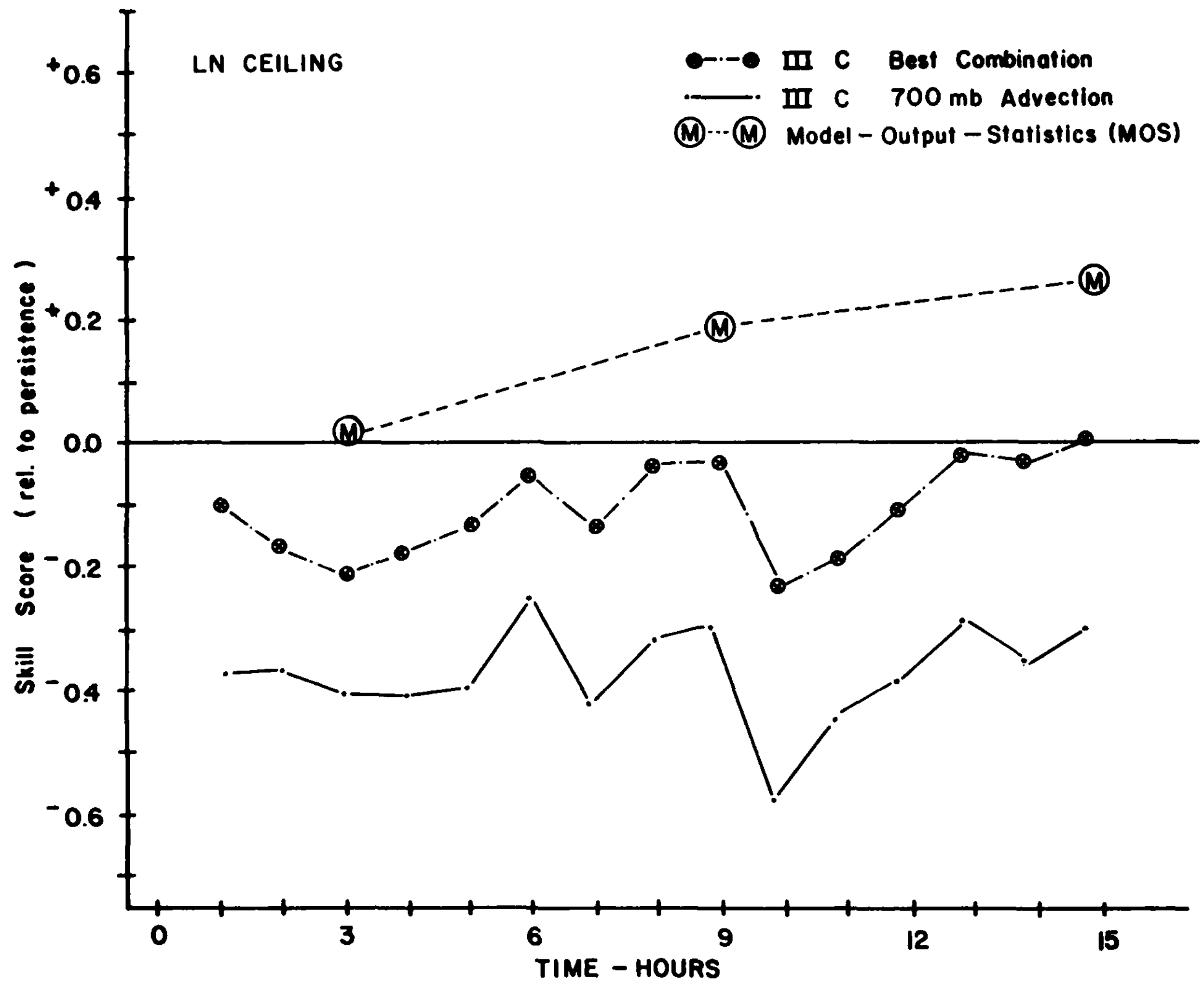

Figure 14. Forecast Skill Scores (Relative to Persistence) for Experiments IIIB and IIIC: Ceiling Height

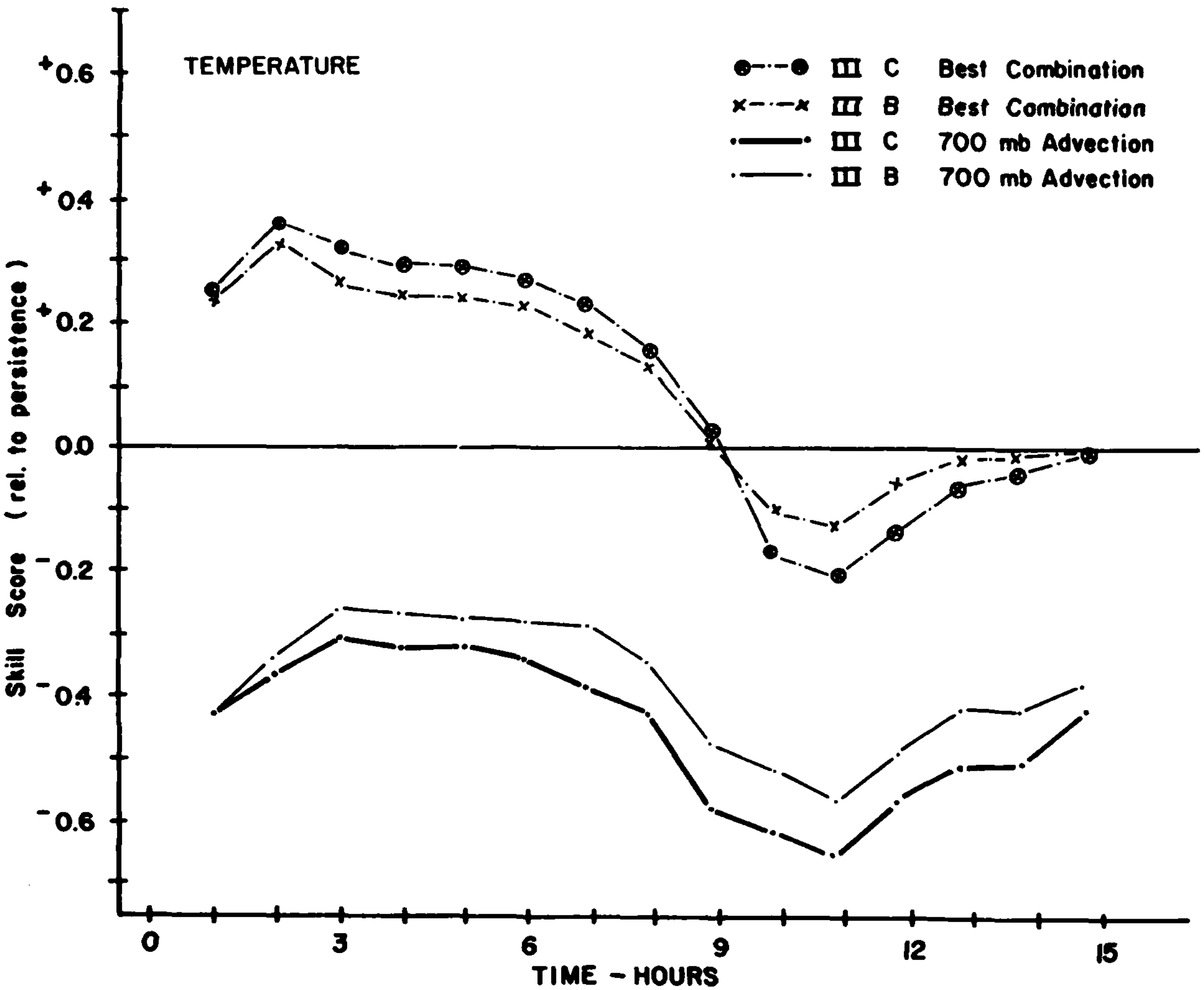

Figure 15. Forecast Skill Scores (Relative to Persistence) for Experiments IIIB and IIIC: Temperature

Table 2. Comparison of Forecast Experiments IIIB and IIIC for 0300 UT and 1500 UT Forecasts, RMS Persistence Error and Forecast Skill Scores

1-4 h Change-Advection Forecasts ($\overline{500}$ mb)								
	0300 UT				1500 UT			
	IIIB		IIIC		IIIB		IIIC	
Parameter	Pers.	Fcst	Pers.	Fcst	Pers.	Fcst	Pers.	Fcst
Cloud Amount	(.67)	-.01	(.67)	+.04	(.54)	-.54	(.54)	-.13
Vector Wind	(2.55)	+.14	(2.55)	+.14	(3.16)	+.01	(3.16)	+.01
Wind Speed	(1.55)	-.01	(1.55)	-.01	(1.56)	-.09	(1.56)	-.12
Ln Visbibility	(.38)	-.02	(.39)	+.00	(.60)	-.03	(.62)	-.18
Ln Ceiling	--	--	(.55)	-.17	--	--	(.69)	-.28
Dew Point	(1.90)	+.12	--	--	(1.33)	-.50	--	--
Temperature	(1.74)	-.01	(1.74)	+.17	(2.84)	+.38	(2.84)	+.39
5-9 h Advection Forecasts ($\overline{500}$ mb)								
	0300 UT				1500 UT			
	IIIB		IIIC		IIIB		IIIC	
Parameter	Pers.	Fcst	Pers.	Fcst	Pers.	Fcst	Pers.	Fcst
Cloud Amount	(1.06)	+.21	(1.06)	+.39	(.79)	-.19	(.79(	-.06
Vector Wind	(4.12)	+.21	(4.12)	+.17	(4.42)	+.21	(4.42)	+.19
Wind Speed	(2.17)	+.12	(2.17)	+.11	(2.12)	-.06	(2.12)	-.06
Ln Visibility	(.74)	+.08	(.77)	+.02	(.84)	+.14	(.86)	-.02
Ln Ceiling	--	--	(.84)	-.09	--	--	(1.01)	-.07
Dew Point	(3.27)	+.25	--		(2.40)	+.10		--
Temperature	(2.98)	-.13	(2.98)	-.22	(3.74)	-.38	(3.[illegible])	-.39

better at night, unchanged in the day, and the 5-9-hour advection forecasts worse at both times.

When the forecasts using the 0.5-degree Barnes analyses did not produce improved forecasts, there was concern that the routines did not perform properly on the independent data. For a little more insight, computations were made for the spatial variability and analysis errors of the two experiments, with the results shown in Table 3. The first two columns show that, for wind and temperature, the higher resolution analyses have noticeably higher spatial variability, as would be expected. For cloud amount, the situation is reversed, but this is almost certainly because the range in Experiment IIIB is -5 to 45 and only 0 to 30 in Experiment IIIC. The visibility analyses cannot be directly compared because Experiment IIIB is in miles, while Experiment IIIF is rms of the logarithm. The analysis errors of the next two columns are based on the 0-h forecast errors at the 12 forecast locations. Except for the cloud amount, the Experiment IIIC analyses seem to be slightly worse (about 2 percent), but the difference is negligible. The Barnes analysis software provides rms analysis errors for all stations used (typically 330-380 stations), and in the next column, these values are seen to

Table 3. Spatial Variability and Analysis Errors for 1-Degree McIDAS Analyses (IIIB) and 0.5-Degree Barnes Analyses (IIIC)

	RMS Variability		Analysis Errors			
			12 Stations		All Sta.	Devel.
Parameter	IIIB	IIIC	IIIB	IIIC	IIIC	IIIC
Cloud Amount (cat)	1.32	0.98	0.56	0.31	0.32	0.30
U-component (mps)	2.79	3.27	--	--	1.04	1.32
V-component (mps)	2.59	3.65	--	--	1.09	1.39
Vector Wind (mps)	3.80	4.90	1.97	2.01	1.50	1.85
Ln Visibility	4.39*	0.99	0.39	0.40	0.40	0.40
Ln Ceiling	--	1.57	--	0.44	0.48	0.44
Dewpoint (C)	5.65	6.16	0.94	0.96	0.94	0.96
Temperature (C)	5.89					

*based on visibility in miles, not natural logarithm.

be quite similar to those based on only 12 forecast stations. The final column indicates the rms errors for the dependent December analysis tests, and these values are quite consistent with the others. As a final test, the rms analysis errors for each forecast case and each parameter are shown in Figure 16. From this figure, the analyses appear to be stable and consistent in quality from case to case and there seems to be no indication that the analysis procedure did not perform as well on the independent March 1983 data as it did on the dependent December 1983 data.

These results indicate that the new analysis routine did produce what appeared to be better mesoscale analyses. The finer scale analyses were better defined and there was better temporal continuity. There are several possible explanations of why the "improved" analyses did not lead to improved advection forecasts. First, the smallest-scale disturbances may be largely orographic (stationary) in nature. Further, these disturbances may have too short a lifetime to be successfully forecast by advection. There is also a possibility that the bilinear interpolation scheme used in the forecast procedure may be too coarse to capture all available information. Higher order interpolation might be better.

5. DISCUSSION

When this program of advection-forecast-technique development began, the basic premise was that traveling mesoscale disturbances were a major cause of short-period changes in surface weather conditions. Some modest success has been achieved through tests of various advection flows, through development of change-advection procedures, and other enhancements to the advection technique. A summary of qualitative results is shown in Table 4, which indicates the gain (or loss) in skill that resulted from the introduction of various modifications.

Obviously, not all attempts at improvement were successful, but overall, there has been encouraging progress. At the present time, the best advection techniques show skill better than both MOS and persistence for periods out to about 6 hours for cloud cover, vector wind, and visibility. These results do indicate that information from the hourly aviation weather network can be used to improve forecasts objectively through the use of modified forms of advection.

While we have been encouraged by the steady improvement in forecast skill scores through enhancement of the advection technique, the levels of skill, with values like +0.05 to +0.20, might appear low. An important question is how high must the skill level be before the technique can be considered useful. The first point to consider is that these skill scores are based on rms errors, and a more realistic measure is the "variance." A skill score of +0.30 means that about

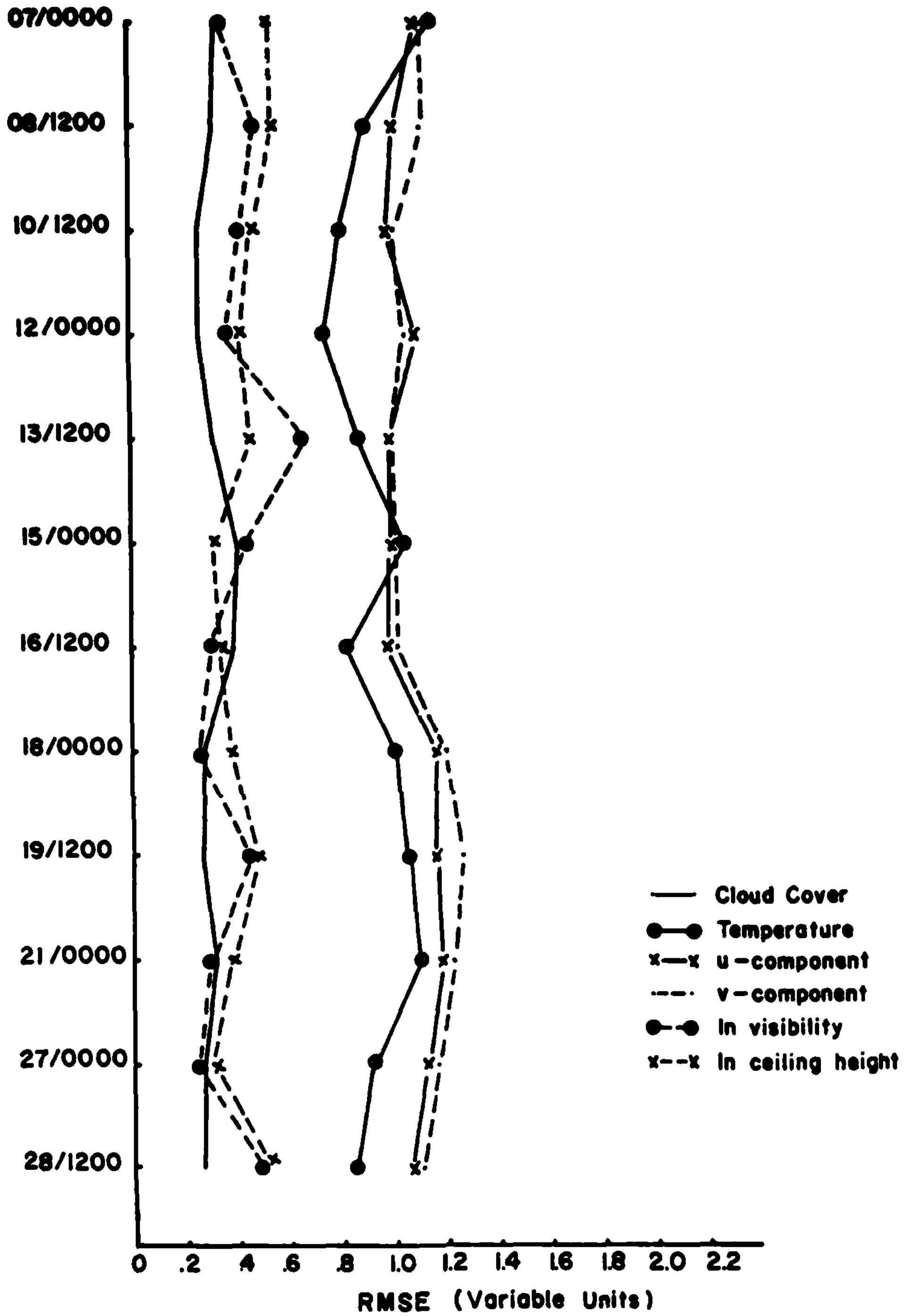

Figure 16. Variation of Root-Mean-Square (RMS) Analysis Error for Cases Comprising the March 1983 Independent Data Set

Table 4. Results of Forecast Experiments II Through IIIC: Changes Relative to Simple 700-mb Advection

Better Forecasts	Worse Forecasts
Change-advection (0-3 hours)	Change-advection (5-15 hours)
700-500 mb space-averaged flow	850-300 mb vertically integrated flow
500 mb space-averaged flow	
850 mb flow, double advection (temperature and dewpoint)	850 mb flow (double advection) (clouds, visibility, winds)
Modification for diurnal changes	
Adjustment of initial data (winds, dewpoint)	
0.5-degree Barnes-type analyses (clouds, temperature using change advection)	0.5-degree Barnes-type analyses (wind, visibility)

50 percent of the temporal change variance (analogous to spectral "power") has been correctly forecast. And, a skill score of +0.20 means 36 percent of the variance correctly forecast. From this point of view, +0.2 might mean an important part of the variance correctly forecast, and +0.3 might mean a majority forecast correctly.

An interactive forecast experiment was recently completed at AFGL[11] when a number of forecast aids were evaluated to determine usefulness to the forecaster. The MOS forecasts were the primary objective guidance for the vector wind, and the 5-10-h forecasts were about 30 percent better than persistence. The forecasters considered this guidance for wind useful 67 percent of the time. By contrast, the ceiling and cloud-amount category forecasts for MOS were only 5-10 percent better than persistence, and this guidance was useful only 53 and 58 percent of the time. Considering the variance correctly forecast and also the forecast aid evaluation, we can suggest that objective guidance should begin to be useful when skill scores reach +0.15 to +0.20 and be

11. Chisholm, D.A., and Jackson, A.J. (1984) An Assessment of Interactive Graphics Processing in Short-Range Terminal Weather Forecasting, AFGL-TR-84-0029, AD A142706.

definitely useful when they reach +0.30. After some effort, the scores for some parameters and some time periods are reaching these levels. Some questions to consider are: "Realistically, how much more improvement can we expect?" and "How should we best design future improvements?"

To begin to answer these questions, we should start by considering a basic forecast limitation due to the variability that cannot be resolved by analysis grids. Let us say there is a prediction Q_f and that Q_o is observed. Further, that Q_o is composed of Q_g, the grid-scale value, and Q_s is the subgrid scale disturbance. The rms forecast error F is computed by:

$$F = \left[\overline{(Q_f - Q_g - Q_s)^2} \right]^{1/2} \tag{12}$$

where the $\overline{\quad}$ represents an average over many stations and many cases. The best we can hope for is that the advection technique will perfectly forecast Q_g ($Q_f = Q_g$), leaving some error due to subgrid scale variability. If P is the rms persistence error, the skill score S is

$$S = \frac{P - F}{P} = 1 - \frac{F}{P} . \tag{13}$$

The maximum possible skill score will be Sx, given by

$$Sx = 1 - \frac{\left(\overline{Q_s^2}\right)^{1/2}}{P} . \tag{14}$$

Assuming the rms analysis errors V_s represent subgrid scale forecast errors, then we can use computed values of rms persistence errors to solve Eq. 14 for the maximum skill score. Calculations were made for seven parameters at 3 and 6 hours, and the results are presented in Table 5. Also included in this table are values of the best-combination advection forecast scores. Examining the table, we see that the weather parameters in the table fall into two distinct groups. For cloud cover, vector wind, temperature, and dewpoint, the advection skill scores S_B are all positive, generally about one-fourth to one-third the maximum skill score values. At that point, the advection guidance forecasts would reach the "useful" level. To go much further, one would have to find means to accurately predict development and decay of the disturbances as well as the motion.

On the other hand, developing useful advection forecast techniques for wind speed, visibility, and ceiling height represents a somewhat greater challenge. For these parameters, the present skill scores are near zero, and even if

Table 5. Maximum Skill Scores and Best Skill Scores for 3- and 6-Hour Forecasts

	3 Hours				6 Hours		
	v_s [1]	P [2]	Sx [3]	S_B [4]	P	Sx	S_B
Cloud Cover (cat.)	±0.31	±0.65	.52	+.11	±0.81	.62	+.20
Vector Wind (mps)	±1.81	±3.03	.40	+.11	±4.02	.55	+.19
Wind Speed (mps)	±1.27	±1.63	.22	-.03	± 1.96	.35	-.01
Ln Visibility	±0.39	±0.53	.26	+.02	± 0.73	.47	+.14
Ln Ceiling	±0.44	±0.66	.27	-.16	± 0.87	.45	-.06
Temperature (C)	±0.85	±2.64	.68	+.33	± 3.59	.76	+.27
Dewpoint (C)	±1.12	±1.77	.37	+.05	± 2.54	.56	+.14

1. Subgrid variability of 12 stations (for compatibility with persistence, unmodified data of Experiment IIIA used) $V_s = \overline{(Q_s^2)}^{1/2}$
2. RMS persistence errors at 12 stations
3. Maximum skill score $Sx = 1 - V_s/P = 1 - \frac{\overline{(Q_s^2)}^{1/2}}{P}$
4. Best advection skill score

suggested improvements raised the levels to one-half the maximum level, the forecasts still would not be very useful, especially for periods less than 6 hours. Thus, the first step would be to produce higher resolution analyses and nonlinear interpolation to significantly reduce analysis error. In addition, satellite and radar information would be needed to help fill in detail in sparse data regions. Even with greatly impproved analyses, improvements in the forecast may not be as great as might be expected because the recovered small-scale disturbances may have lifetimes as short as 1-3 hours or less. However, wind speed, visibility, and ceiling are very important forecast parameters for aviation, and small positive skill scores would probably still be appreciated. To provide maximum information on these difficult parameters, it may be desirable to convert the advection forecasts from absolute values to probabilities. In the long-run, high-resolution numerical prediction models offer the most hope to solve the short-range forecast problem for these particularly difficult parameters.

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Appendix

Tables of Forecast Scores for Experiments IIIB and IIIC

Techniques

Adv. + Diur.	Advection with modification for diurnal changes
Change-Advs.	Change-Advection
$\overline{500}$	500-mb space-averaged advection flow
700 mb	700-mb advection flow
$\overline{5}$*7	Double advection; 500-mb space-average flow advecting 700-mb advection flow
$\overline{5}$*8	Double advection; 500-mb space-average flow advecting 850-mb advection flow

Table A1. Advection Forecast Experiment IIIB: Skill Scores Relative to Persistence (144 Forecasts) Total Cloud Cover

TOTAL CLOUD COVER (rms category error, 0-3)									
TECHNIQUE/TIME (HR)	0	1	2	3	4	6	9	12	15
Persistence	(±0.00)	(±0.44)	(±0.59)	(±0.65)	(±0.72)	(±0.81)	(±1.05)	(±1.21)	(±1.19)
Persistence+Diur.	(±0.00)	-0.03	-0.01	-0.01	-0.02	+0.00	+0.00	+0.01	+0.01
Advection 700 mb	(±0.56)	-0.50	-0.27	-0.25	-0.18	-0.15	-0.02	+0.04	-0.04
Advection 500	(±0.56)	-0.51	-0.22	-0.14	-0.01	-0.01	+0.04	+0.07	-0.11
Advection 5*7	(±0.56)	-0.50	-0.27	-0.25	-0.20	-0.15	-0.07	+0.02	+0.07
Advection 5*8	(±0.56)	-0.50	-0.25	-0.17	-0.16	-0.19	-0.07	-0.03	0.06
Adv.+Diur. 700 mb	(±0.56)	-0.24	-0.09	-0.04	-0.01	+0.03	+0.12	+0.14	+0.06
Adv.+Diur. 500	(±0.56)	-0.21	+0.00	+0.11	+0.24	+0.20	+0.20	+0.14	-0.03
Adv.+Diur 5*7	(±0.56)	-0.24	-0.09	-0.04	-0.03	+0.01	+0.04	+0.11	+0.00
Adv.+Diur. 5*8	(±0.56)	-0.27	-0.07	+0.02	+0.00	-0.08	+0.05	+0.11	+0.08
Change-Adv. 700 mb	(±0.00)	-0.04	-0.19	-0.32	-0.44	-0.57	-0.76	-0.96	-1.04
Change-Adv. 500	(±0.00)	-0.04	-0.16	-0.25	-0.37	-0.51	-0.70	-1.00	-1.09
Change-Adv. 5*7	(±0.00)	-0.04	-0.20	-0.32	-0.44	-0.56	-0.74	-0.93	-1.05
Change-Adv. 5*8	(±0.00)	-0.07	-0.25	-0.42	-0.58	-0.78	-1.02	-1.32	-1.47
NMC-MOS	(±0.00)	XXX	XXX	-0.28	XXX	XXX	+0.28	XXX	+0.28
Chg-Adv.+Diur. 700 mb	(±0.00)	-0.04	-0.10	-0.10	-0.14	-0.09	-0.18	-0.22	+0.03
Chg-Adv.+Diur. 500	(±0.00)	-0.05	-0.07	-0.03	-0.04	-0.02	-0.12	-0.33	-0.15
Chg-Adv.+Diur. 5*7	(±0.00)	-0.04	-0.10	-0.10	-0.15	-0.10	-0.19	-0.22	+0.05
Chg-Adv.+Diur. 5*8	(±0.00)	-0.07	-0.15	-0.19	-0.25	-0.32	-0.50	-0.64	-0.56

Table A2. Advection Forecast Experiment IIIB: Skill Scores Relative to Persistence (144 Forecasts) Vector Wind

	VECTOR WIND (rms error--mps--in parentheses)								
TECHNIQUE/TIME (HR)	0	1	2	3	4	6	9	12	15
Persistence	(±0.00)	(±1.84)	(±2.79)	(±3.03)	(±3.57)	(±4.02)	(±4.79)	(±5.99)	(±6.32)
Persistence+Diur.	(±0.83)	+0.00	+0.03	+0.04	+0.03	+0.03	+0.04	+0.03	+0.02
Advection 700 mb	(±1.97)	-0.18	0.03	+0.08	+0.12	+0.15	+0.19	+0.25	+0.26
Advection $\overline{500}$	(±1.97)	-0.17	0.02	+0.11	+0.14	+0.18	+0.27	+0.31	+0.30
Advection $\overline{5}$*7	(±1.97)	-0.18	0.03	+0.08	+0.12	+0.15	+0.22	+0.29	+0.26
Advection $\overline{5}$*8	(±1.97)	-0.18	0.02	+0.07	+0.10	+0.13	+0.22	+0.24	+0.23
Adv.+Diur. 700 mb	(±1.97)	-0.20	0.03	+0.09	+0.13	+0.16	+0.20	+0.25	+0.27
Adv.+Diur. $\overline{500}$	(±1.97)	-0.19	0.02	+0.11	+0.15	+0.19	+0.27	+0.31	+0.31
Adv.+Diur. $\overline{5}$*7	(±1.97)	-0.20	0.03	+0.09	+0.13	+0.17	+0.22	+0.29	+0.27
Adv.+Diur. $\overline{5}$*8	(±1.97)	-0.20	0.02	+0.07	+0.10	+0.13	+0.22	+0.24	+0.23
Change-Adv. 700 mb	(±0.83)	+0.04	+0.02	+0.03	+0.06	-0.01	-0.13	-0.17	-0 22
Change-Adv. $\overline{500}$	(±0.83)	+0.05	+0.04	+0.06	+0.08	+0.02	-0.07	-0.12	-0.20
Change-Adv. $\overline{5}$*7	(±0.83)	+0.04	+0.02	+0.03	+0.06	-0.01	-0.13	-0.16	-0.24
Change-Adv. $\overline{5}$*8	(±0.83)	+0.04	+0.02	+0.03	+0.03	-0.06	-0.18	-0.27	-0.38
Chg-Adv.+Diur. 700 mb	(±0.83)	+0.03	+0.01	+0.01	+0.03	-0.03	-0.11	-0.12	-0.17
Chg-Adv.+Diur. $\overline{500}$	(±0.83)	+0.04	+0.03	+0.05	+0.05	+0.00	-0.05	-0.03	-0.13
Chg-Adv.+Diur $\overline{5}$*7	(±0.83)	+0.03	+0.01	+0.01	+0.03	+0.03	-0.10	-0.11	-0.18
Chg-Adv.+Diur. $\overline{5}$*8	(±0.83)	+0.03	+0.01	+0.01	+0.01	-0.05	-0.14	-0.20	-0.30
NMC-MOS	(±0.00)	XXX	XXX	+0.01	XXX	XXX	+0.30	XXX	+0.42

Table A3. Advection Forecast Experiment IIIB: Skill Scores Relative to Persistence (144 Forecasts) Wind Speed

	WIND SPEED (rms error--mps--in parentheses)								
TECHNIQUE/TIME (HR)	0	1	2	3	4	6	9	12	15
Persistence	(±0.00)	(±1.13)	(±1.47)	(±1.63)	(±1.90)	(±1.96)	(±2.50)	(±2.74)	(±3.05)
Persistence+Diur.	(±0.53)	+0.05	+0.07	+0.03	+0.04	-0.01	+0.01	+0.03	+0.09
Advection 700 mb	(±1.32)	-0.33	-0.27	-0.18	-0.13	-0.10	+0.11	+0.07	+0.15
Advection $\overline{500}$	(±1.32)	-0.29	-0.26	-0.12	-0.11	-0.09	+0.18	+0.16	+0.18
Advection $\overline{5}$*7	(±1.32)	-0.33	-0.26	-0.17	-0.14	-0.10	+0.15	+0.03	+0.11
Advection $\overline{5}$*8	(±1.32)	-0.29	-0.20	-0.13	-0.13	-0.09	+0.13	+0.05	+0.03
Adv.+Diur. 700 mb	(±1.32)	-0.38	-0.25	-0.14	-0.08	-0.03	+0.09	+0.05	+0.19
Adv.+Diur. $\overline{500}$	(±1.32)	-0.34	-0.25	-0.08	-0.05	-0.03	+0.16	+0.14	+0.22
Adv.+Diur. $\overline{5}$*7	(±1.32)	-0.38	-0.24	-0.13	-0.08	-0.03	+0.13	+0.01	+0.14
Adv.+Diur. $\overline{5}$*8	(±1.32)	-0.34	-0.19	-0.10	-0.09	-0.05	+0.10	+0.05	+0.11
Change-Adv. 700 mb	(±0.53)	+0.02	-0.02	-0.09	-0.12	-0.40	-0.62	-0.87	-0.85
Change-Adv. $\overline{500}$	(±0.53)	+0.01	-0.02	-0.05	-0.09	-0.31	-0.56	-0.76	-0.79
Change-Adv. $\overline{5}$*7	(±0.53)	+0.02	-0.02	-0.09	-0.11	-0.40	-0.61	-0.80	-0.83
Change-Adv. $\overline{5}$*8	(±0.53)	+0.02	-0.02	-0.08	-0.13	-0.43	-0.65	-1.04	-1.14
Chg-Adv.+Diur. 700 mb	(±0.53)	+0.01	-0.02	-0.09	-0.09	-0.39	-0.53	-0.72	-0.73
Chg-Adv.+Diur. $\overline{500}$	(±0.53)	+0.00	-0.02	-0.03	-0.08	-0.29	-0.49	-0.62	-0.63
Chg-Adv.+Diur. $\overline{5}$*7	(±0.53)	+0.01	-0.02	-0.08	-0.08	-0.39	-0.52	-0.67	-0.69
Chg-Adv.+Diur. $\overline{5}$*8	(±0.53)	+0.01	-0.02	-0.05	-0.10	-0.40	-0.55	-0.84	-0.98
NMC-MOS	(±0.00)	XXX	XXX	+0.02	XXX	XXX	+0.21	XXX	+0.30

Table A4. Advection Forecast Experiment IIIB: Skill Scores Relative to Persistence (144 Forecasts) Visibility

LN VISIBILITY (rms errors in parentheses)									
TECHNIQUE/TIME (HR)	0	1	2	3	4	6	9	12	15
Persistence	(±0.00)	(±0.35)	(±0.44)	(±0.53)	(±0.63)	(±0.73)	(±0.89)	(±0.93)	(±1.04)
Persistence+Diur.	(±0.00)	+0.01	+0.05	+0.06	+0.05	+0.07	+0.05	-0.05	-0.12
Advection 700 mb	(±0.39)	-0.29	-0.05	+0.02	+0.10	+0.12	+0.07	+0.04	+0.00
Advection $\overline{500}$	(±0.39)	-0.21	-0.01	+0.00	+0.14	+0.13	+0.12	+0.23	+0.19
Advection $\overline{5}$*7	(±0.39)	-0.28	-0.05	+0.01	+0.10	+0.11	+0.09	+0.14	+0.16
Advection $\overline{5}$*8	(±0.39)	-0.20	+0.02	-0.02	-0.04	-0.03	+0.03	+0.21	+0.18
Adv.+Diur. 700 mb	(±0.39)	-0.32	-0.07	+0.01	+0.09	+0.13	+0.09	+0.00	+0.02
Adv.+Diur. $\overline{500}$	(±0.39)	-0.23	-0.04	-0.01	+0.10	+0.14	+0.15	+0.13	+0.08
Adv.+Diur. $\overline{5}$*7	(±0.39)	-0.32	-0.07	+0.01	+0.10	+0.11	+0.11	+0.09	+0.07
Adv.+Diur. $\overline{5}$*8	(±0.39)	-0.23	+0.01	+0.01	-0.04	-0.05	+0.00	+0.03	+0.06
Change-Adv. 700 mb	(±0.00)	+0.04	-0.01	-0.06	-0.07	-0.11	-0.12	-0.39	-0.52
Change-Adv. $\overline{500}$	(±0.00)	+0.01	-0.03	-0.06	-0.02	-0.11	-0.11	-0.17	-0.39
Change-Adv. $\overline{5}$*7	(±0.00)	+0.04	-0.01	-0.05	-0.07	-0.13	-0.14	-0.38	-0.41
Change-Adv. $\overline{5}$*8	(±0.00)	+0.01	-0.07	-0.13	-0.15	-0.17	-0.16	-0.37	-0.47
Chg-Adv.+Diur. 700 m	(±0.00)	+0.01	-0.02	-0.08	-0.10	-0.21	-0.36	-0.73	-0.91
Chg-Adv.+Diur. $\overline{500}$	(±0.00)	-0.01	-0.09	-0.10	-0.08	-0.22	-0.39	-0.62	-0.91
Chg-Adv.+Diur. $\overline{5}$*7	(±0.00)	+0.01	-0.02	-0.08	-0.10	-0.19	-0.36	-0.72	-0.88
Chg-Adv.+Diur. $\overline{5}$*8	(±0.00)	-0.01	-0.09	-0.14	-0.21	-0.29	-0.44	-0.72	-0.87
NMC-MOS	(±0.00)	XXX	XXX	-0.28	XXX	XXX	+0.10	XXX	+0.37

Table A5. Advection Forecast Experiment IIIB: Skill Scores Relative to Persistence (144 Forecasts) Temperature

	TEMPERATURE (rms errors--Celsius--in parentheses)								
TECHNIQUE/TIME (HR)	0	1	2	3	4	6	9	12	15
Persistence	(±0.00)	(±1.28)	(±2.01)	(±2.64)	(±3.10)	(±3.59)	(±3.03)	(±3.19)	(±4.36)
Persistence+Diur.	(±0.00)	+0.19	+0.28	+0.25	+0.24	+0.21	+0.11	+0.05	+0.14
Advection 700 mb	(±0.94)	-0.43	-0.34	-0.27	-0.27	-0.28	-0.48	-0.49	-0.39
Advection $\overline{500}$	(±0.94)	-0.42	-0.32	-0.27	-0.26	-0.27	-0.34	-0.19	-0.21
Advection $\overline{5}*7$	(±0.94)	-0.43	-0.34	-0.27	-0.27	-0.29	-0.47	-0.48	-0.39
Advection $\overline{5}*8$	(±0.94)	-0.30	-0.18	-0.13	-0.14	-0.14	-0.20	-0.05	+0.02
Adv.+Diur. 700 mb	(±0.94)	-0.26	-0.05	+0.01	+0.04	+0.00	-0.33	-0.55	-0.46
Adv.+Diur. $\overline{500}$	(±0.94)	-0.24	-0.02	+0.02	+0.05	+0.03	-0.19	-0.23	-0.26
Adv.+Diur. $\overline{5}*7$	(±0.94)	-0.26	-0.05	+0.01	+0.04	-0.01	-0.32	-0.52	-0.43
Adv.+Diur. $\overline{5}*8$	(±0.94)	-0.12	+0.12	+0.18	+0.17	+0.16	-0.01	-0.06	+0.00
Change-Adv. 700 mb	(±0.00)	+0.22	+0.32	+0.29	+0.24	+0.07	-1.08	-2.62	-2.50
Change-Adv. $\overline{500}$	(±0.00)	+0.22	+0.31	+0.27	+0.22	+0.02	-1.05	-2.52	-2.43
Change-Adv. $\overline{5}*7$	(±0.00)	+0.22	+0.32	+0.29	+0.24	+0.07	-1.09	-2.60	-2.55
Change-Adv. $\overline{5}*8$	(±0.00)	+0.23	+0.33	+0.27	+0.20	+0.01	-1.09	-2.49	-2.39
Chg-Adv.+Diur. 700 m	(±0.00)	+0.20	+0.27	+0.26	+0.25	+0.23	-0.07	-0.56	-0.49
Chg-Adv.+Diur. $\overline{500}$	(±0.00)	+0.20	+0.27	+0.25	+0.24	+0.17	-0.18	-0.54	-0.39
Chg-Adv.+Diur. $\overline{5}*7$	(±0.00)	+0.20	+0.27	+0.26	+0.25	+0.23	-0.06	-0.45	-0.39
Chg-Adv.+Diur. $\overline{5}*8$	(±0.00)	+0.21	+0.29	+0.25	+0.20	+0.13	-0.21	-0.53	-0.38
NMC-MOS	(±0.00)	XXX	XXX	0.36	XXX	+0.50	+0.46	+0.38	+0.38

Table A6. Advection Forecast Experiment IIIB: Skill Scores Relative to Persistence (144 Forecasts) Dewpoint Temperature

	DEWPOINT TEMPERATURE (*rms errors--Celsius--in parentheses*)								
TECHNIQUE/TIME (HR)	0	1	2	3	4	6	9	12	15
Persistence	(±0.00)	(±1.03)	(±1.58)	(±1.77)	(±2.02)	(±2.54)	(±3.43)	(±4.29)	(±4.94)
Persistence+Diur.	(±0.00)	XXX	XXX	XXX	XXX	XXX	XXX	XXX	XXX
Advection 700 mb	(±1.24)	-0.36	-0.06	+0.00	+0.00	-0.01	+0.05	-0.01	-0.03
Advection $\overline{500}$	(±1.24)	-0.42	-0.05	-0.02	-0.05	+0.14	+0.23	+0.23	+0.24
Advection $\overline{5}$*7	(±1.24)	-0.36	-0.06	-0.01	+0.01	+0.01	+0.11	+0.05	+0.02
Advection $\overline{5}$*8	(±1.24)	-0.29	-0.01	+0.05	+0.03	+0.12	+0.18	+0.17	+0.20
Adv.+Diur. 700 mb	(±1.24)	XXX	XXX	XXX	XXX	XXX	XXX	XXX	XXX
Adv.+Diur. $\overline{500}$	(±1.24)	XXX	XXX	XXX	XXX	XXX	XXX	XXX	XXX
Adv.+Diur. $\overline{5}$*7	(±1.24)	XXX	XXX	XXX	XXX	XXX	XXX	XXX	XXX
Adv.+Diur. $\overline{5}$*8	(±1.24)	XXX	XXX	XXX	XXX	XXX	XXX	XXX	XXX
Change-Adv. 700mb	(±0.00)	-0.08	-0.09	-0.08	-0.17	-0.23	-0.26	-0.28	-0.32
Change-Adv. $\overline{500}$	(±0.00)	-0.10	-0.11	-0.08	-0.18	-0.25	-0.31	-0.28	-0.29
Change-Adv. $\overline{5}$*7	(±0.00)	-0.08	-0.09	-0.07	-0.17	-0.25	-0.27	-0.28	-0.34
Change-Adv. $\overline{5}$*8	(±0.00)	-0.09	-0.11	-0.13	-0.24	-0.33	-0.42	-0.41	-0.48
Chg-Adv.+Diur. 700 m	(±0.00)	XXX	XXX	XXX	XXX	XXX	XXX	XXX	XXX
Chg-Adv.+Diur $\overline{500}$	(±0.00)	XXX	XXX	XXX	XXX	XXX	XXX	XXX	XXX
Chg-Adv.+Diur $\overline{5}$*7	(±0.00)	XXX	XXX	XXX	XXX	XXX	XXX	XXX	XXX
Chg-Adv.+Diur $\overline{5}$*8	(±0.00)	XXX	XXX	XXX	XXX	XXX	XXX	XXX	XXX
NMC-MOS	(±0.00)	XXX	XXX	-0.02	XXX	+0.25	+0.49	+0.44	+0.53

Table A7. Advection Forecast Experiment IIIC: Skill Scores Relative to Persistence (144 Forecasts) Total Cloud Cover

	TOTAL CLOUD COVER (rms category error, 0-3)								
TECHNIQUE/TIME (HR)	0	1	2	3	4	6	9	12	15
Persistence	(±0.00)	(±0.44)	(±0.59)	(±0.65)	(±0.72)	(±0.81)	(±1.05)	(±1.21)	(±1.19)
Persistence+Diur.	(±0.00)	-0.03	-0.01	-0.01	-0.02	+0.00	+0.00	+0.01	+0.01
Advection 700 mb	(±0.31)	-0.14	-0.06	-0.08	-0.01	+0.10	+0.13	+0.19	+0.06
Advection $\overline{500}$	(±0.31)	-0.15	+0.04	+0.11	+0.22	+0.17	+0.20	+0.10	+0.00
Advection $\overline{5}*7$	(±0.31)	-0.14	-0.06	-0.09	-0.04	+0.05	+0.12	+0.17	-0.01
Advection $\overline{5}*8$	(±0.31)	-0.14	+0.05	+0.11	+0.06	+0.02	+0.07	+0.10	+0.09
Adv.+Diur. 700 mb	(±0.31)	-0.23	-0.10	-0.10	-0.05	+0.10	+0.12	+0.19	+0.04
Adv.+Diur. $\overline{500}$	(±0.31)	-0.22	-0.00	+0.10	+0.22	+0.17	+0.18	+0.10	-0.02
Adv.+Diur. $\overline{5}*7$	(±0.31)	-0.23	-0.10	-0.11	-0.07	+0.00	+0.10	+0.16	-0.03
Adv.+Diur. $\overline{5}*8$	(±0.31)	-0.24	-0.01	+0.07	+0.04	-0.01	+0.05	+0.11	+0.09
Change-Adv. 700 mb	(±0.00)	-0.01	-0.06	-0.06	-0.11	-0.10	-0.15	-0.10	-0.06
Change-Adv. $\overline{500}$	(±0.00)	+0.00	-0.04	-0.01	-0.04	-0.03	-0.13	-0.29	-0.22
Change-Adv. $\overline{5}*7$	(±0.00)	-0.01	-0.06	-0.07	-0.12	-0.11	-0.17	-0.11	-0.18
Change-Adv. $\overline{5}*8$	(±0.00)	-0.02	-0.10	-0.13	-0.22	-0.29	-0.42	-0.52	-0.57
Chg-Adv.+Diur. 700 m	(±0.00)	-0.03	-0.04	-0.03	-0.07	-0.04	-0.11	-0.01	+0.00
Chg-Adv.+Diur. $\overline{500}$	(±0.00)	-0.03	-0.02	+0.00	-0.01	+0.00	-0.08	-0.20	-0.07
Chg-Adv.+Diur. $\overline{5}*7$	(±0.00)	-0.03	-0.03	-0.03	-0.07	-0.05	-0.09	+0.00	+0.00
Chg-Adv.+Diur. $\overline{5}*8$	(±0.00)	-0.05	-0.06	-0.09	-0.15	-0.24	-0.40	-0.45	-0.40
NMC-MOS	(±0.00)	XXX	XXX	-0.28	XXX	XXX	+0.28	XXX	+0.28

Table A8. Advection Forecast Experiment IIIC: Skill Scores Relative to Persistence (144 Forecasts) Vector Wind

VECTOR WIND (rms errors--mps--in parentheses)									
TECHNIQUE/TIME (HR)	0	1	2	3	4	6	9	12	15
Persistence	(±0.00)	(±1.84)	(±2.79)	(±3.03)	(±3.57)	(±4.02)	(±4.79)	(±5.99)	(±6.32)
Persistence+Diur.	(±0.83)	+0.00	+0.03	+0.04	+0.03	+0.03	+0.04	+0.03	+0.02
Advection 700 mb	(±2.01)	-0.15	-0.01	+0.07	+0.10	+0.11	+0.09	+0.16	+0.15
Advection $\overline{500}$	(±2.01)	-0.15	+0.01	+0.12	+0.15	+0.14	+0.23	+0.29	+0.28
Advection $\overline{5}*7$	(±2.01)	-0.15	-0.01	+0.07	+0.10	+0.11	+0.14	+0.24	+0.21
Advection $\overline{5}*8$	(±2.01)	-0.15	+0.02	+0.08	+0.10	+0.12	+0.20	+0.19	+0.18
Adv.+Diur. 700 mb	(±2.01)	-0.17	-0.01	+0.07	+0.11	+0.12	+0.10	+0.17	+0.15
Adv.+Diur. $\overline{500}$	(±2.01)	-0.18	+0.01	+0.12	+0.16	+0.15	+0.24	+0.29	+0.29
Adv.+Diur. $\overline{5}*7$	(±2.01)	-0.17	-0.01	+0.07	+0.11	+0.12	+0.15	+0.25	+0.22
Adv.+Diur. $\overline{5}*8$	(±2.01)	-0.16	+0.02	+0.08	+0.11	+0.12	+0.20	+0.20	+0.18
Change-Adv. 700 mb	(±0.83)	+0.03	+0.03	+0.03	+0.05	-0.03	-0.18	-0.23	-0.33
Change-Adv. $\overline{500}$	(±0.83)	+0.03	+0.04	+0.05	+0.07	-0.04	-0.06	-0.13	-0.21
Change-Adv. $\overline{5}*7$	(±0.83)	+0.03	+0.03	+0.03	+0.05	-0.03	-0.18	-0.24	-0.35
Change-Adv. $\overline{5}*8$	(±0.83)	+0.03	+0.03	+0.02	+0.04	-0.04	-0.18	-0.28	-0.42
Chg-Adv.+Diur. 700 m	(±0.83)	+0.03	+0.03	+0.01	+0.01	-0.04	-0.15	-0.15	-0.26
Chg-Adv.+Diur. $\overline{500}$	(±0.83)	+0.03	+0.04	+0.04	+0.06	-0.03	-0.03	-0.05	-0.13
Chg-Adv.+ Diur. $\overline{5}*7$	(±0.83)	+0.03	+0.02	+0.01	+0.03	-0.03	-0.14	-0.16	-0.26
Chg-Adv.+Diur. $\overline{5}*8$	(±0.83)	+0.03	+0.03	+0.00	+0.01	-0.05	-0.14	-0.21	-0.32
NMC-MOS	(±0.00)	XXX	XXX	+0.01	XXX	XXX	+0.30	XXX	+0.42

Table A9. Advection Forecast Experiment IIIC: Skill Scores Relative to Persistence (144 Forecasts) Wind Speed

	WIND SPEED (rms errors--mps--in parentheses)								
TECHNIQUE/TIME (HR)	0	1	2	3	4	6	9	12	15
Persistence	(±0.00)	(±1.13)	(±1.47)	(±1.63)	(±1.90)	(±1.96)	(±2.50)	(±2.74)	(±3.05)
Persistence+Diur.	(±0.53)	+0.05	+0.07	+0.03	+0.04	-0.01	+0.01	+0.03	+0.09
Advection 700 mb	(±1.39)	-0.28	-0.27	-0.13	-0.09	-0.11	+0.06	+0.02	+0.08
Advection $\overline{500}$	(±1.39)	-0.25	-0.22	-0.07	-0.03	-0.11	+0.16	+0.14	+0.19
Advection $\overline{5}*7$	(±1.39)	-0.28	-0.27	-0.13	-0.10	-0.10	+0.14	+0.00	+0.06
Advection $\overline{5}*8$	(±1.39)	-0.28	-0.18	-0.08	-0.09	-0.05	+0.14	+0.07	+0.04
Adv.+Diur. 700 mb	(±1.39)	-0.32	-0.24	-0.09	-0.04	-0.04	+0.06	+0.01	+0.11
Adv.+Diur. $\overline{500}$	(±1.39)	-0.29	-0.21	-0.04	+0.01	-0.05	+0.15	+0.12	+0.22
Adv.+Diur. $\overline{5}*7$	(±1.39)	-0.32	-0.24	-0.10	-0.04	-0.04	+0.13	+0.02	+0.10
Adv.+Diur. $\overline{5}*8$	(±1.39)	-0.32	-0.16	-0.05	-0.05	-0.01	+0.12	+0.07	+0.12
Change-Adv. 700 mb	(±0.53)	+0.00	-0.05	-0.12	-0.14	-0.43	-0.61	-0.94	-1.10
Change-Adv. $\overline{500}$	(±0.53)	+0.00	-0.04	-0.08	-0.10	-0.31	-0.55	-0.81	-0.84
Change-Adv. $\overline{5}*7$	(±0.53)	+0.00	-0.04	-0.12	-0.14	-0.43	-0.59	-0.92	-1.06
Change-Adv. $\overline{5}*8$	(±0.53)	+0.00	-0.04	-0.11	-0.13	-0.42	-0.65	-1.07	-1.22
Chg-Adv.+Diur 700 m	(±0.53)	-0.01	-0.05	-0.11	-0.13	-0.43	-0.55	-0.74	-0.91
Chg-Adv.+Diur. $\overline{500}$	(±0.53)	+0.00	-0.04	-0.07	-0.09	-0.29	-0.48	-0.63	-0.65
Chg-Adv.+Diur. $\overline{5}*7$	(±0.53)	-0.01	-0.05	-0.11	-0.13	-0.43	-0.53	-0.72	-0.84
Chg-Adv.+Diur. $\overline{5}*8$	(±0.53)	-0.01	-0.03	-0.10	-0.12	-0.43	-0.58	-0.88	-1.00
NMC-MOS	(±0.00)	XXX	XXX	+0.02	XXX	XXX	+0.21	XXX	+0.30

Table A10. Advection Forecast Experiment IIIC: Skill Scores Relative to Persistence (144 Forecasts) LN Visibility

LN VISIBILITY (rms errors in parentheses)									
TECHNIQUE/TIME (HR)	0	1	2	3	4	6	9	12	15
Persistence	(±0.00)	(±0.36)	(±0.46)	(±0.55)	(±0.65)	(±0.75)	(±0.91)	(±0.95)	(±1.07)
Persistence+Diur.	(±0.00)	+0.01	+0.01	+0.02	+0.01	+0.02	+0.01	-0.01	-0.02
Advection 700 mb	(±0.40)	-0.47	-0.32	-0.26	-0.12	-0.09	+0.14	-0.24	-0.08
Advection $\overline{500}$	(±0.40)	-0.39	-0.26	-0.25	-0.10	-0.02	+0.02	+0.03	+0.11
Advection $\overline{5}*7$	(±0.40)	-0.47	-0.32	-0.28	-0.15	-0.12	-0.13	-0.17	-0.08
Advection $\overline{5}*8$	(±0.40)	-0.23	-0.10	-0.16	-0.18	-0.22	-0.21	-0.05	-0.07
Adv.+Diur. 700 mb	(±0.40)	-0.83	-0.30	-0.17	+0.01	+0.07	+0.09	+0.26	+0.05
Adv.+Diur. $\overline{500}$	(±0.40)	-0.67	-0.24	-0.15	+0.00	+0.06	+0.13	+0.20	+0.05
Adv.+Diur. $\overline{5}*7$	(±0.40)	-0.82	-0.31	-0.18	+0.00	+0.06	+0.08	+0.26	+0.04
Adv.+Diur. $\overline{5}*8$	(±0.40)	-0.41	-0.08	-0.06	+0.00	+0.03	+0.11	+0.19	+0.10
Change-Adv. 700 mb	(±0.00)	+0.00	-0.13	-0.20	-0.27	-0.40	-0.59	-1.23	-1.44
Change-Adv. $\overline{500}$	(±0.00)	+0.02	-0.11	-0.16	-0.17	-0.26	-0.33	-0.53	-0.71
Change-Adv. $\overline{5}*7$	(±0.00)	+0.00	-0.13	-0.20	-0.27	-0.45	-0.58	-1.26	-1.43
Change-Adv. $\overline{5}*8$	(±0.00)	+0.01	-0.14	-0.25	-0.36	-0.48	-0.58	-1.06	-1.15
Chg-Adv.+Diur. 700 m	(±0.00)	-0.01	-0.11	-0.21	-0.33	-0.63	-1.12	-1.74	-2.38
Chg-Adv.+diur. $\overline{500}$	(±0.00)	+0.04	-0.09	-0.15	-0.17	-0.36	-0.73	-1.25	-1.72
Chg-Adv.+Diur. $\overline{5}*7$	(±0.00)	-0.01	-0.12	-0.21	-0.32	-0.68	-1.14	-1.80	-2.35
Chg-Adv.+Diur. $\overline{5}*8$	(±0.00)	+0.02	-0.13	-0.26	-0.37	-0.59	-0.92	-1.61	-1.94
NMC-MOS	(±0.00)	XXX	XXX	-0.29	XXX	XXX	0.09	XXX	+0.37

Table A11. Advection Forecast Experiment IIIC: Skill Scores Relative to Persistence (144 Forecasts)
LN Ceiling

	LN CEILING (rms errors in parentheses)								
TECHNIQUE/TIME (HR)	0	1	2	3	4	6	9	12	15
Persistence	(±0.00)	(±0.47)	(±0.54)	(±0.66)	(±0.78)	(±0.89)	(±1.04)	(±1.10)	(±1.14)
Persistence+Diur.	(±0.00)	XXX	XXX	XXX	XXX	XXX	XXX	XXX	XXX
Advection 700 mb	(±0.44)	-0.38	-0.37	-0.41	-0.42	-0.26	-0.30	-0.38	-0.30
Advection $\overline{500}$	(±0.44)	-0.26	-0.16	-0.22	-0.18	-0.06	-0.04	-0.11	+0.00
Advection $\overline{5}*7$	(±0.44)	-0.38	-0.38	-0.43	-0.41	-0.27	-0.32	-0.35	-0.21
Advection $\overline{5}*8$	(±0.44)	-0.27	-0.16	-0.16	-0.27	-0.19	-0.28	-0.18	-0.17
Adv. +Diur. 700 mb	(±0.44)	XXX	XXX	XXX	XXX	XXX	XXX	XXX	XXX
Adv. +Diur. $\overline{500}$	(±0.44)	XXX	XXX	XXX	XXX	XXX	XXX	XXX	XXX
Adv. +Diur. $\overline{5}*7$	(±0.44)	XXX	XXX	XXX	XXX	XXX	XXX	XXX	XXX
Adv. +Diur. $\overline{5}*8$	(±0.44)	XXX	XXX	XXX	XXX	XXX	XXX	XXX	XXX
Change-Adv. 700 mb	(±0.00	-0.10	-0.17	-0.22	-0.29	-0.46	-0.73	-1.27	-1.83
Change-Adv. $\overline{500}$	(±0.00)	-0.09	-0.21	-0.27	-0.28	-0.42	-0.35	-0.64	-0.85
Change-Adv. $\overline{5}*7$	(±0.00)	-0.10	-0.17	-0.22	-0.29	-0.47	-0.71	-1.22	-1.70
Change-Adv. $\overline{5}*8$	(±0.00)	-0.10	-0.20	-0.27	-0.36	-0.46	-0.76	-1.22	-1.58
Chg-Adv. +Diur. 700 m	(±0.00)	XXX	XXX	XXX	XXX	XXX	XXX	XXX	XXX
Chg-Adv. +Diur. $\overline{500}$	(±0.00)	XXX	XXX	XXX	XXX	XXX	XXX	XXX	XXX
Chg-Adv. +Diur. $\overline{5}*7$	(±0.00)	XXX	XXX	XXX	XXX	XXX	XXX	XXX	XXX
Chg-Adv. +Diur. $\overline{5}*8$	(±0.00)	XXX	XXX	XXX	XXX	XXX	XXX	XXX	XXX
NMC-MOS	(±0.00)	XXX	XXX	+0.01	XXX	XXX	+0.19	XXX	+0.26

Table A12. Advection Forecast Experiment IIIC: Skill Scores Relative to Persistence (144 Forecasts) Temperature

TEMPERATURE (rms errors--Celsius--in parentheses)									
TECHNIQUE/TIME (HR)	0	1	2	3	4	6	9	12	15
Persistence	(±0.00)	(±1.28)	(±2.01)	(±2.64)	(±3.10)	(±3.59)	(±3.03)	(±3.19)	(±4.36)
Persistence+Diur.	(±0.00)	+0.19	-0.28	+0.25	+0.24	+0.21	+0.11	+0.05	+0.14
Advection 700 mb	(±0.96)	-0.43	-0.36	-0.31	-0.32	-0.34	-0.58	-0.57	-0.43
Advection $\overline{500}$	(±0.96)	-0.43	-0.33	-0.28	-0.27	-0.31	-0.38	-0.25	-0.23
Advection $\overline{5}$*7	(±0.96)	-0.43	-0.36	-0.31	-0.32	-0.34	-0.55	-0.55	-0.45
Advection $\overline{5}$*8	(±0.96)	-0.32	-0.20	-0.15	-0.17	-0.19	-0.27	-0.12	+0.00
Adv. +Diur 700 mb	(±0.96)	-0.23	-0.06	-0.02	+0.00	-0.07	-0.44	-0.64	-0.51
Adv. +Diur. $\overline{500}$	(±0.96)	-0.21	-0.02	+0.02	+0.04	-0.03	-0.25	-0.29	-0.28
Adv. +Diur. $\overline{5}$*7	(±0.96)	-0.23	-0.06	+0.02	-0.01	-0.08	-0.41	-0.58	-0.50
Adv. +Diur. $\overline{5}$*8	(±0.96)	-0.11	+0.12	+0.16	+0.14	+0.10	-0.08	-0.13	-0.01
Change-Adv. 700 mb	(±0.00)	+0.25	+0.35	+0.33	+0.30	+0.14	-0.99	-2.47	-2.41
Change-Adv. $\overline{500}$	(±0.00)	+0.25	+0.35	+0.33	+0.32	+0.18	-0.93	-2.33	-2.27
Change-Adv. $\overline{5}$*7	(±0.00)	+0.25	+0.35	+0.33	+0.30	+0.13	-1.01	-2.50	2.47
Change-Adv. $\overline{5}$*8	(±0.00)	+0.25	+0.36	+0.32	+0.26	+0.08	-1.04	-2.44	-2.31
Chg-Adv. +Diur. 700 m	(±0.00)	+0.20	+0.29	+0.29	+0.30	+0.27	-0.02	-0.44	-0.40
Chg-Adv. +Diur. $\overline{500}$	(±0.00)	+0.20	+0.28	+0.29	+0.31	+0.25	-0.07	-0.43	-0.35
Chg-Adv. +Diur. $\overline{5}$*7	(±0.00)	+0.20	+0.29	+0.29	+0.30	+0.27	-0.02	-0.38	-0.37
Chg-Adv. +Diur. $\overline{5}$*8	(±0.00)	+0.21	+0.30	+0.27	+0.25	+0.17	-0.19	-0.57	-0.39
NMC-MOS	(±0.00)	XXX	XXX	+0.36	XXX	+0.50	+0.46	+0.38	+0.38