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The Air Weather Service Winter Trajectory Test Program

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ABSTRACT

The Winter Trajectory Test Program was conducted as part of the Air Weather Service Forecaster Assistance Program. The objective of this test was to determine if three-dimensional trajectories derived from the output of the Air Force Global Weather Central's six-level model are useful in the preparation of terminal forecasts. Headquarters Air Weather Service personnel evaluated forecasts prepared at detachments located in the central and eastern United States and modified some of these forecasts on the basis of trajectory information. The application of trajectory data improved the four-month verification of the terminal forecasts by 3.1%. Test procedures are discussed, and objective rules developed for the evaluation are presented.

1. Introduction

In recent years Air Weather Service (AWS) and other agencies of the scientific community have expended considerable resources on numerical techniques in an effort to forecast the future positions of synoptic-scale weather systems. This emphasis has produced numerical models that predict quite accurately mid-tropospheric flow patterns. However, over the past decade improvement in day-to-day terminal weather forecasts has not been as significant as the improvement in the numerical prediction of upper-air features. The structure of the short-lived, small-scale disturbances associated with these large-scale dynamic systems is extremely complex, and the effects of these multi-scale systems on terminal weather conditions vary with each location. Presently, the best way to incorporate local effects into the forecast product is to call on the experience of the local terminal forecaster. Local data sources such as radar and wind recorders coupled with an intimate knowledge of terrain, pollution sources, and other local effects make the terminal forecaster a vital link in developing and preparing mesoscale forecasts from synoptic-scale products.

Fletcher (1956) stated that a major role of the station forecaster is to interpret and modify the machine output to produce forecasts for his customers, and to record the reasoning for his modifications so that the laboratory meteorologist can develop improved programs for the machine. He urged that a greater communication between the researcher and forecaster be developed to incorporate the terminal forecaster's knowledge into research and development efforts. Extracting information from numerical products for the express use of specific terminals, incorporating the forecaster's knowledge of local effects into the terminal forecast, and instilling a sense of professional pride in the terminal forecaster are the primary functions of the AWS Forecaster Assistance Program.

Recently, several investigators (Danielsen, 1966; Nagle *et al.*, 1966; Hansen and Thompson, 1965; Rogers and Sherr, 1967) found a high correlation between the integrated vertical motion and the history of air parcels and resulting cloud patterns. Their results suggest that trajectory data may be useful to the forecaster in predicting terminal weather conditions. Studying the future movement of air parcels introduces the forecaster to Lagrangian forecasting techniques. It permits forecasters to make numerous useful inferences that are not easily derived from the products currently available. Consequently, a winter trajectory test was scheduled for the period 15 November 1967 through 1 March 1968. Forecasters at Headquarters AWS used trajectory data to evaluate official terminal forecasts (TAFs) prepared at seven U. S. bases. The remaining portion of this paper will discuss the procedures, objective rules and results of this program.

2. Trajectory model

The trajectories used in the AWS Winter Trajectory Test Program were constructed from 6-hr trajectory segments computed for the Air Force Global Weather Central (AFGWC) Cloud Forecasting Model (hereinafter called the cloud model). The cloud model follows individual air parcels through their three-dimensional paths and modifies temperature and moisture according to adiabatic and pseudoadiabatic considerations. The output includes cloud, temperature and moisture forecast fields for 850, 700, 500 and 300 mb. A detailed description of the cloud model is given by Edson (1966).

The cloud-model trajectories forecast temperature and moisture by a kinematic procedure. Each air parcel is moved by the horizontal and vertical velocity components supplied at 2-hr increments from the AFGWC Six-Level Forecast Model. Output trajectories in the form of 6-hr segments are constructed backward from each grid point for the four forecast pressure levels. Backward trajectories are computed because programming is simplified and it is desirable to have the forecast temperature and moisture specified at grid points.

Each 2-hr increment of the 6-hr trajectories is computed in the following manner. For clarity, the displacement along a single coordinate is discussed. Given an air parcel at a point X at time t, with a velocity component U, the first approximation at $t-2$ hr is

$$X_{t-2}^{1}=X_{t}-\Delta t U_{t}.$$

The superscript on X_{t-2} refers to the number of the approximation, and Δt refers to the 2-hr forecast increment. A second approximation of X_{t-2} is computed by averaging the final velocity U_t and the velocity U_{t-2}^{1} at the first approximation of X_{t-2}^{1}, i.e.,

$$X_{t-2}^{2}=X_{t}-\tfrac{1}{2}(U_{t}+U_{t-2}^{1})\Delta t.$$

Succeeding approximations are computed until the convergence limit of 0.07 grid units is reached; that is, for the νth approximation

$$|X_{t-2}^{\nu}-X_{t-2}^{\nu-1}|<0.07.$$

For the vertical p dimension a convergence limit of 5 mb is used.

Values of temperature and moisture are assigned to the initial points of the 0- to 6-hr trajectories by three-dimensional interpolation in the analysis fields. The initial temperature and moisture are adjusted along the path of the parcel assuming dry-adiabatic conditions. If the condensation pressure level is reached while the parcel is ascending, the parcel's temperature and moisture are adjusted pseudoadiabatically. The model assumes that all condensed moisture falls out in the form of precipitation. By this procedure the forecast fields at $t=6$ hr are developed. The forecast fields at $t=6$ hr are then used for three-dimensional interpolation to assign temperature and moisture values at the initial points of the 6–12 hr trajectories. The above procedures are repeated to obtain 12-hr forecast fields of temperature and moisture. This sequential 6-hr operation is continued to determine forecast fields at 18, 24, 36 and 48 hr.

Since only 6-hr trajectories are computed by the cloud model, a method was programmed to determine trajectories for any geographic location rather than for grid points, and to combine these short 6-hr trajectories into continuous trajectories of lengths of 12, 18, 24, 36 and 48 hr. Then, interpolation in the cloud-model forecast fields yields predictions of temperature and dew point at these geographic locations.

The AFGWC Six-Level Forecast Model produces vertical velocities and quasi-geostrophic winds, but the important ageostrophic components are not available when computing the cloud-model trajectories. However, verification of trajectory-based temperature and moisture forecasts (Barnum, 1966; Kuhnsman, 1967) suggests that the trajectories are reasonable approximations to the true path of the parcel.

3. Objective forecasting rules

During the first month of the winter evaluation, Headquarters AWS forecasters (hereinafter called "trajectory forecasters") designed a set of simple objective forecasting rules to apply to the trajectory data. Because of the varied types of synoptic situations which develop during the winter season, the set of forecasting rules had to be simple to cover the spectrum of weather situations. These rules ideally should be applied only to the levels for which trajectory data are available. In many situations changes in moisture and vertical motion at 850 mb yield information about changes in cloud cover at nearby levels. However, the same set of objective rules may predict clear conditions at the trajectory level and overcast conditions when applied to a slightly higher or lower level. This apparent inconsistency is due to the variability of the moisture content in the vertical. For example, a large high-pressure ridge may be associated with subsidence and drying at 850 mb, whereas overcast stratus conditions may exist simultaneously at a lower level.

An excellent aid would be a chart showing the integrated and instantaneous forecast vertical motion (Martin, 1966). The latter provides additional information about the parcel's final motion which can be different than the integrated value. However, the instantaneous vertical-motion fields were not available, so in a few cases the final sign of a parcel's vertical motion was estimated from the synoptic situation. In these cases the vertical-motion objective rules were modified to account for an obvious sign change during the final segment of the trajectory. The reader is reminded that the vertical-motion values used were from the AFGWC Six-Level Forecast Model, and that the magnitude and definition of vertical-motion fields differ among the various numerical models.

The forecasting rules were as follows:

Rule 1: Amount of cloud cover. The integrated vertical motion and the dew-point spread $T-T_d$ were used to determine the predicted cloud amount. If the integrated vertical motion of a parcel was forecast upward with velocities >0.5 mb hr^{-1}, overcast conditions were predicted if the corresponding forecast $T-T_d$ was less than 3C, or broken conditions were forecast if the corresponding forecast $T-T_d$ was between 3 and 6C. If the integrated vertical motion of the parcel was forecast downward at velocities >0.5 mb hr^{-1}, then prior existing cloud conditions were forecast to improve accordingly.

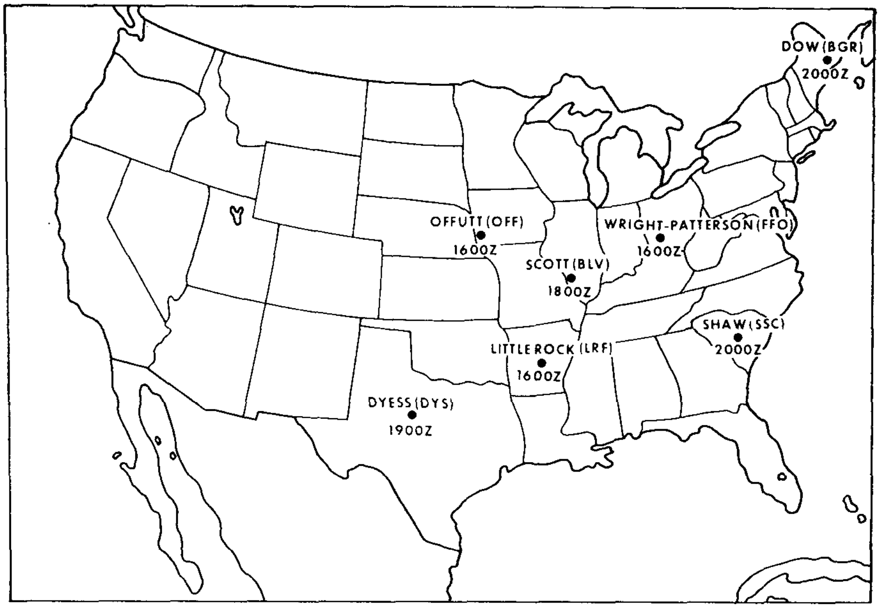

FIG. 1. Locations of Air Force Bases whose TAFs were evaluated. Station designators and initial times of official TAFs are shown.

Rule 2: Advection of cloud cover. In the ambiguous range of integrated vertical motion between ± 0.5 mb hr^{-1}, advection and forecast moisture were the primary tools used for determining cloud cover. However, before upstream cloud conditions could be advected over a station, the trajectory forecaster had to distinguish between diurnal and synoptic cloud features. Also, the forecast moisture had to agree with the advected cloud condition. Advection was an extremely useful tool when the upstream cloud mass was associated with a synoptic feature.

Rule 3: Precipitation. The integrated vertical motion and $T-T_d$ were used as predictors for forecasting precipitation. If the parcel's moisture content was forecast to be saturated and the integrated upward vertical motion >1 mb hr^{-1}, precipitation was forecast. Precipitation patterns were advected if the integrated vertical motion was upward but weaker than 1 mb hr^{-1} and/or the predicted $T-T_d$ was not saturated and not greater than 6C. When precipitation was observed upstream, the precipitation type (i.e., intermittent vs continuous) was advected and forecast to occur over the station.

Rule 4: Form of precipitation. A simple rule-of-thumb proposed by Donaldson and Shafer (1966) for the eastern United States was used to predict whether precipitation would reach the surface in frozen or liquid form. For locations near sea level they found: 1) snow with 850-mb temperatures <-2C; 2) a mixture of snow, sleet, and rain (including freezing rain) with 850-mb temperatures between 0C and -2C; and 3) rain with 850-mb temperatures >0C.

By late November it was apparent that changes in the local weather at Shaw AFB (SSC), Dow AFB (BGR) and Wright-Patterson AFB (FFO) were not revealed by the trajectory data. Mountains west of SSC and BGR induce drying and subsidence of air parcels arriving from a westerly direction. At FFO, the Great Lakes add low-level moisture to parcels passing over the base from a northerly direction. The objective rules were of little value when the parcels were influenced by these local conditions. Therefore, special rules were designed for these bases whenever the paths of parcels were influenced by local topographical features, and the TAFs were modified accordingly. For example, at SSC rapid clearing conditions were incorporated into the TAF whenever the final trajectory component veered from a southerly or southeasterly direction to a westerly or northwesterly direction, even though the parcel's forecast moisture content may have been near saturation.

4. Operational procedures

Fig. 1 shows the geographic locations and station designators of the seven bases whose official 24-hr TAFs were evaluated by trajectory data. The initial times of the official TAFs also are shown. Once daily, trajectory forecasters received trajectory data for seven bases. Each trajectory message contained a forecast temperature and dew point for each pressure level, as well as the pressure of the initial point of each parcel. Knowing the parcel's initial and final pressure permitted the trajectory forecaster to compute the integrated vertical displacement along the parcel's path. The trajectories were computed from the 1200 GMT data

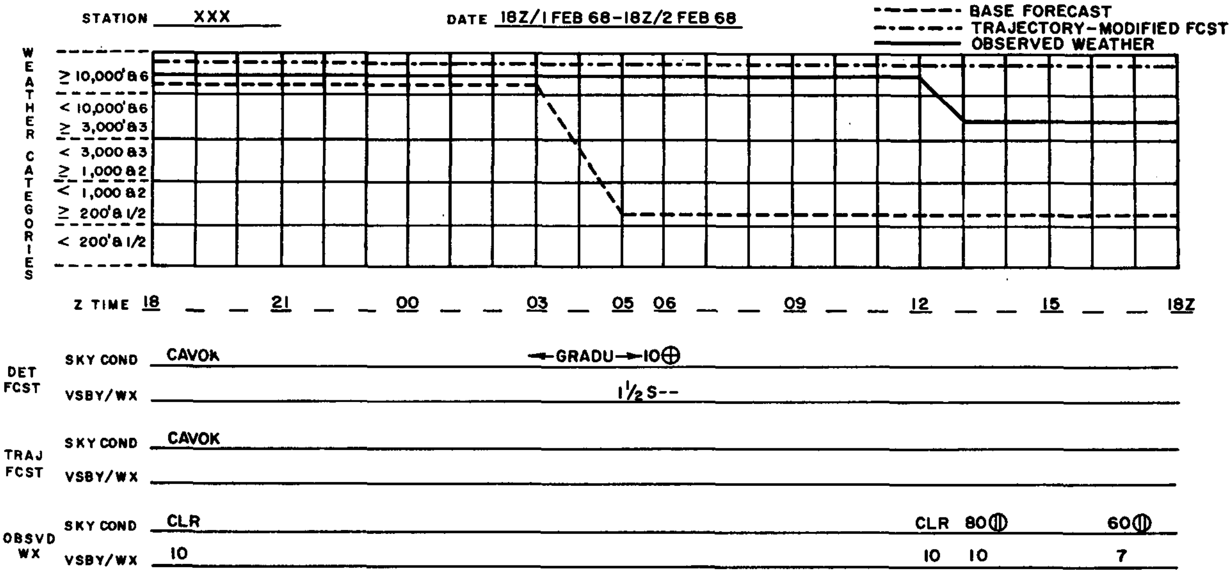

FIG. 2. Sample profile verification sheet. In the weather categories, the heights are in feet and visibilities are in miles.

base and were received at Scott AFB 6–8 hr after data time.

The evaluation was conducted at the Scott AFB Base Weather Station. After the official TAF was received via teletype, the trajectory data and those synoptic charts available to the base forecaster when the original TAF was prepared were used to evaluate and, if necessary, modify the forecast. TAFs were evaluated and modified as soon as possible after they were received. Since the trajectory forecasters were not at these bases, they assumed that, if they had been there, they would have prepared the same forecast as the base forecaster. That is, they would have had access to local studies, an understanding of local climatology, and an appreciation of local weather influences of systems passing their station. The variation of individual forecasting ability is a reasonable objection to this assumption. Consequently, rules were established and every effort was made to be objective when using the trajectory data. The cardinal rule was that an official TAF could be modified only if the trajectory data did not agree with the forecast conditions. Being as objective as possible eliminated, or at least reduced, the temptation to "second guess" the base forecaster.

The procedural rules established by the trajectory forecasters were:

1) The first two hours of the TAF were never modified.

2) Trajectory forecasters did not have access to teletype data later than those available to the detachment forecasters.

3) Trajectory forecasters had access to only those facsimile charts which the detachment forecaster had available when he prepared his TAF. For example, the 1200 GMT surface analysis and the 1300 GMT nephanalysis were used to evaluate the 1600 GMT TAFs.

4) Visibility forecasts were modified when precipitation forecasts were modified. Specifically, these forecasts were modified when: (a) precipitation in the form of rain was not forecast by the base but should have been according to the trajectory data (these modifications usually reduced the visibilities to 2–3 mi in light rain and possibly fog); (b) the official TAF predicted snow, but the trajectory data indicated that the form of precipitation would be rain, higher visibilities being forecast in these cases; (c) the official TAF predicted rain, but the trajectory data indicated that snow was more probable, lower visibilities being forecast in these cases.

5) Haze or fog predicted by the base was always included in the modified forecast.

6) If the weather approaching or moving away from a terminal produced low ceilings and visibilities, the modified TAF retained the ceilings and visibilities forecast by the station. Only the timing on improving or deteriorating these conditions was changed. For example, if the base forecast ceilings and visibilities to improve, but trajectories indicated that improvement would not take place, the low conditions forecast by the base were extended for as long as the trajectory data indicated that little change would occur.

7) Base forecasts of ceilings <3000 ft and visibilities <3 mi *were not* modified except as noted in 4) and 6) above.

5. Verification results

a. Verification procedures

Each official TAF and trajectory forecast was verified against the hourly observed weather. This hourly verification scheme revealed forecast detail such as the timing of weather changes. The ceiling and visibility

TABLE 1. November ceiling and visibility forecast results.

Station	Number of forecast hours	Number of forecast hours unchanged	Unchanged forecast hours correct	Unchanged forecast hours wrong	Number of forecast hours modified	Number of modified hours correct	Number of modified hours official TAF correct
BLV	288	233	200	33	55	35	6
OFF	288	228	177	51	60	42	8
LRF	288	218	178	40	70	44	13
FFO	288	213	157	56	75	22	35
DYS	288	245	207	39	42	23	14
BGR	288	270	183	87	18	4	14
SSC	288	233	177	56	55	8	36
Monthly total	2016	1641	1279	362	375	178	126

November overall verification: Trajectory 72.3%; Official 69.7%

TABLE 2. December ceiling and visibility forecast results.

Station	Number of forecast hours	Number of forecast hours unchanged	Unchanged forecast hours correct	Unchanged forecast hours wrong	Number of forecast hours modified	Number of modified hours correct	Number of modified hours official TAF correct
BLV	408	311	206	105	97	52	22
OFF	408	319	191	128	89	44	33
LRF	408	327	219	108	81	28	23
FFO	408	324	194	130	84	26	27
DYS	408	377	284	93	31	26	3
BGR	408	366	274	92	42	13	6
SSC	408	351	242	109	57	22	14
Monthly total	2856	2375	1610	765	481	211	128

December overall verification: Trajectory 63.8%; Official 60.9%

categories followed those in the current AWS verification program and are shown in Fig. 2. Each day official TAFs and corresponding trajectory-modified forecasts were plotted on profile sheets. The official TAF (dashed line) was recorded on the first line below the profile, the trajectory forecast (dash-dot line) on the second line, and the observed weather (solid line) on the third line. The official and/or trajectory hourly forecasts were scored as correct if they predicted the same category that was observed. For example, in Fig. 2 the official TAF was correct from 1800 to 0300 GMT and the trajectory forecast was correct from 1800 to 1200 GMT.

Precipitation forecasts were verified for four 6-hr periods of the 24-hr forecast. The official or trajectory-modified forecast was credited with a correct precipitation forecast if it correctly predicted the occurrence or nonoccurrence of precipitation. The precipitation form (frozen or liquid) was not included in the occurrence or nonoccurrence verification scheme. Additional statistics were compiled for these cases.

b. Ceiling- and visibility-forecast results

The monthly verifications of hourly forecasts for each base are shown in Tables 1–4. Statistics are included on the unchanged and modified forecasts. At the bottom of each table the monthly statistics for the seven bases are totaled and the overall verification percentages for the trajectory and official TAFs are presented. The overall verification for the trajectory forecasts is found by dividing the sum of the totals of columns 4 and 7 by the total of column 2. The overall verification for the official TAFs is found by using the above formula with the column 7 total replaced by the column 8 total.

The magnitude of trajectory improvement increased from November to December and from December to January (Tables 1–3). In February (Table 4) the improvement was approximately the same as the November level. At least three factors accounted for the low improvement score for November, i.e., trajectory forecasters 1) were not familiar with the trajectory concept, 2) were not acquainted with local influences at SSC, BGR and FFO, and 3) were unable to improve good terminal forecasts.

By mid-December the local influences at SSC, BGR and FFO had been identified and rules had been formulated to account for parcel direction. With the exception of FFO in December, the trajectory data improved the correct-category verification statistics at the three problem bases for the remaining three months of the evaluation.

In February the trajectory improvement in the overall verification statistics decreased to 2.4%, com-

TABLE 3. January ceiling and visibility forecast results.

Station	Number of forecast hours	Number of forecast hours unchanged	Unchanged forecast hours correct	Unchanged forecast hours wrong	Number of forecast hours modified	Number of modified hours correct	Number of modified hours official TAF correct
BLV	528	406	223	183	122	62	22
OFF	528	453	319	134	75	40	6
LRF	528	456	264	192	72	38	16
FFO	528	453	330	123	75	40	17
DYS	528	482	303	179	46	11	2
BGR	528	446	293	153	82	30	20
SSC	528	495	383	112	33	15	3
Monthly total	3696	3191	2115	1076	505	236	86

January overall verification: Trajectory 63.6%; Official 59.5%

TABLE 4. February ceiling and visibility forecast results.

Station	Number of forecast hours	Number of forecast hours unchanged	Unchanged forecast hours correct	Unchanged forecast hours wrong	Number of forecast hours modified	Number of modified hours correct	Number of modified hours official TAF correct
BLV	480	391	291	100	89	52	12
OFF	480	423	290	133	57	28	24
LRF	480	383	295	88	97	45	34
FFO	480	381	261	120	99	61	26
DYS	480	435	350	85	45	5	25
BGR	480	410	303	107	70	23	21
SSC	480	463	399	64	17	13	4
Monthly total	3360	2886	2189	697	474	227	146

February overall verification: Trajectory 71.9%; Official 69.5%

parable with the November value. It is believed that the principal reason for this decrease was the substantial rise in the overall base verification from 59.5% in January to 69.5% in February. Two other factors influenced the skill of trajectory forecasting during February:

1) A blocking ridge remained entrenched over the western United States during most of February. This persistent ridging blocked or modified many of the Pacific systems which normally move through the Midwest (Posey, 1968).

2) Trajectory forecasters unsuccessfully attempted to forecast the onset, movement and dissipation of Gulf stratus at DYS with 850-mb trajectory data. These results emphasize the problem of extrapolating 850-mb data to lower levels. However, a forecaster acquainted with the genesis and character of Gulf stratus and aware of local influences at DYS may be able to make excellent use of 850-mb trajectory data.

c. Refinement of forecasting rules

In November trajectory data were used to modify 19% of the total base forecasts. In December this figure dropped to 17% and in January and February to 14%. These trends were due to a better understanding of local influences and further refinement of the forecasting rules. Although February and November's improvements were approximately equal, the number of modified base forecast hours decreased to 14% in February from 19% in November. In other words, this refinement resulted in an equivalent improvement for a smaller percentage of modified hours.

d. Winter-test summary

Table 5 presents the four-month totals for each base. Columns 9 and 10 are derived from the same formulas used for the overall verification percentages in Tables 1–4. The bases are ranked according to the resulting improvement due to the integration of trajectory data into daily forecast procedures. The largest improvement was at BLV where trajectory data improved official TAFs by 8.2%. Also, the 363 trajectory-modified forecast hours at BLV represented the largest number among the seven bases. These facts are attributed to the trajectory forecasters' knowledge of BLV's local influences on transitory weather systems. Since the forecast rules were developed and applied by Hq AWS personnel, a substantially higher forecast improvement at BLV should be expected. It is reasonable to expect that forecasters "on the scene" at the remaining bases and using trajectory techniques would refine or develop

Table 5. Four-month ceiling and visibility forecast results.

Station	Number of forecast hours	Number of forecast hours unchanged	Unchanged forecast hours correct	Unchanged forecast hours wrong	Number of forecast hours modified	Number of modified hours correct	Number of modified hours official TAF correct	Overall trajectory correct	Overall official TAF correct	Forecast improvement
BLV	1704	1341	920	421	363	201	62	65.8%	57.6%	8.2%
OFF	1704	1423	977	446	281	154	71	66.4%	61.6%	4.8%
LRF	1704	1384	956	428	320	155	86	65.2%	61.2%	4.0%
FFO	1704	1371	942	429	333	149	105	64.0%	61.4%	2.6%
DYS	1704	1540	1144	396	164	65	44	70.9%	69.7%	1.2%
BGR	1704	1492	1053	439	212	70	61	65.9%	65.4%	0.5%
SSC	1704	1542	1201	341	162	58	47	73.8%	73.7%	0.1%
Total	11928	10093	7193	2900	1835	852	486	67.4%	64.3%	3.1%

additional forecast rules to improve verification scores for their locations.

At the bottom of Table 5 the four-month totals are summed and presented as the total winter-test statistics. The overall official TAF verification for four months of evaluation was 64.3% while the corresponding trajectory forecast verification was 67.4%. Thus, for the four months of the winter evaluation, the use of trajectory data resulted in a 3.1% improvement of the official TAFs. Standard significance tests show that the trajectory-modified forecasts are significantly better than the corresponding official forecasts at the 0.1% level. Although numerically small, the four-month improvement of 3.1% represents a substantial gain in terminal-forecast verification when compared with the available statistics of past AWS performance. Statistics evaluated from two AWS wings for March 1955 and March 1967 indicate that terminal forecasts prepared for the 3- and 12-hr verification periods had improved by only 6% over a 12-yr period, a period when numerical prediction was integrated into daily forecast procedures.

The overall trajectory-modified forecast improvement at each base varied inversely with the percentage of correct-category official TAFs. Apparently, a level is reached where trajectory data will no longer improve official forecasts. This level is primarily controlled by the accuracy of the numerical model from which the trajectory data are derived. However, trajectory data correctly indicated that a change was necessary in 73.5% (this percentage being found from Table 5 by dividing the difference of the totals of columns 6 and 8 by the total of column 6) of the modified forecasts, showing definite skill in selecting the poorer TAFs.

Table 6. Four-month observed weather and verification of the trajectory-modified forecasts by category.

Limits of ceiling and visibility category	Percentage of observed weather	Percentage of trajectory-modified forecasts changed	Percentage of correct trajectory-modified forecasts
≥10,000 ft and 6 mi	57.6	27.5	57.9
<10,000 ft and 6 mi ≥ 3000 ft and 3 mi	16.8	40.9	21.6
< 3000 ft and 3 mi ≥ 1000 ft and 2 mi	12.2	18.2	12.9
< 1000 ft and 2 mi ≥ 200 ft and ½ mi	12.0	10.8	7.6
< 200 ft and ½ mi	1.4	2.6	0.0

Table 6 shows additional four-month verification statistics. In Table 6, column 1 is the ceiling and visibility limits for each category, column 2 the percentage of hourly weather observed in each category during the four months of the program, column 3 the percentage of trajectory-modified forecasts changed from each category, and column 4 the percentage of correct trajectory-modified forecasts in each category.

The statistics in Table 6 show that 74.4% of the weather for the seven bases was observed as being above 3000 ft and 3 mi. Thus, the observed weather from November–February was often favorable for the application of objective rules at the 850-mb level. Column 4 of Table 6 shows that approximately 80% of the correct trajectory-modified forecasts verified for ceiling and visibility above 3000 ft and 3 mi. The major portion of the remaining 20% were cases where trajectory data indicated that low conditions should develop earlier or persist later than the official TAFs suggested. Column 3 of Table 6 lends credence to the objectivity of the evaluation; more than two-thirds of the modified forecasts involved official forecasts calling for conditions

Table 7. Trajectory-modified precipitation forecast results.

Month	Number of modified forecasts	Trajectory-modified forecasts correct	Official TAF correct
November	17	8	9
December	31	23	8
January	34	21	13
February	36	19	17
Four-month total	118	71	47
Overall forecast verification	—	84.4%	83.1%

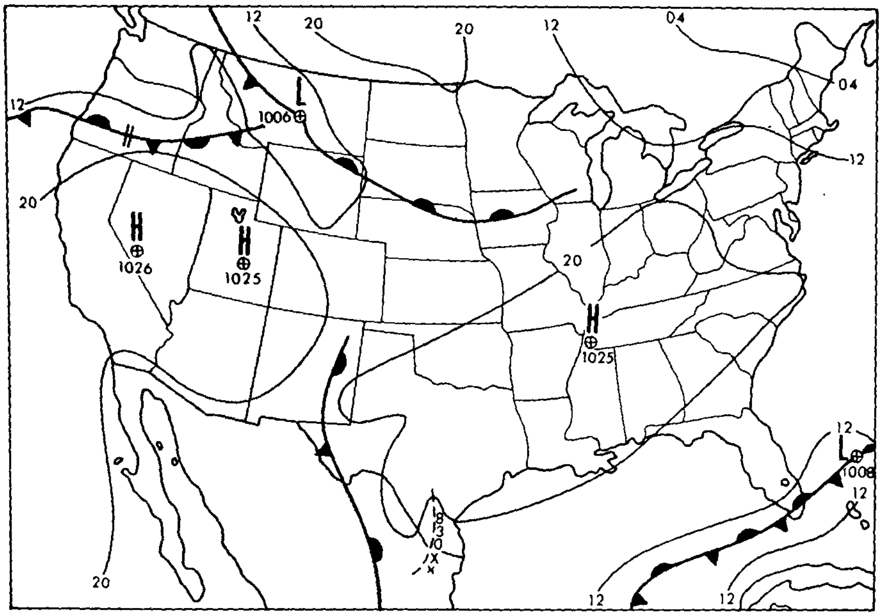

FIG. 3. Surface chart for 1200 GMT 19 February 1968.

above 3000 ft and 3 mi. One would have expected a high percentage of changes in the region above 3000 ft if the objective rules and procedures discussed in Section 3 had been closely followed.

e. Precipitation-forecast results

Table 7 presents the monthly and total precipitation statistics for the winter-test period. Precipitation forecasts were verified for 6-hr periods, the statistics being

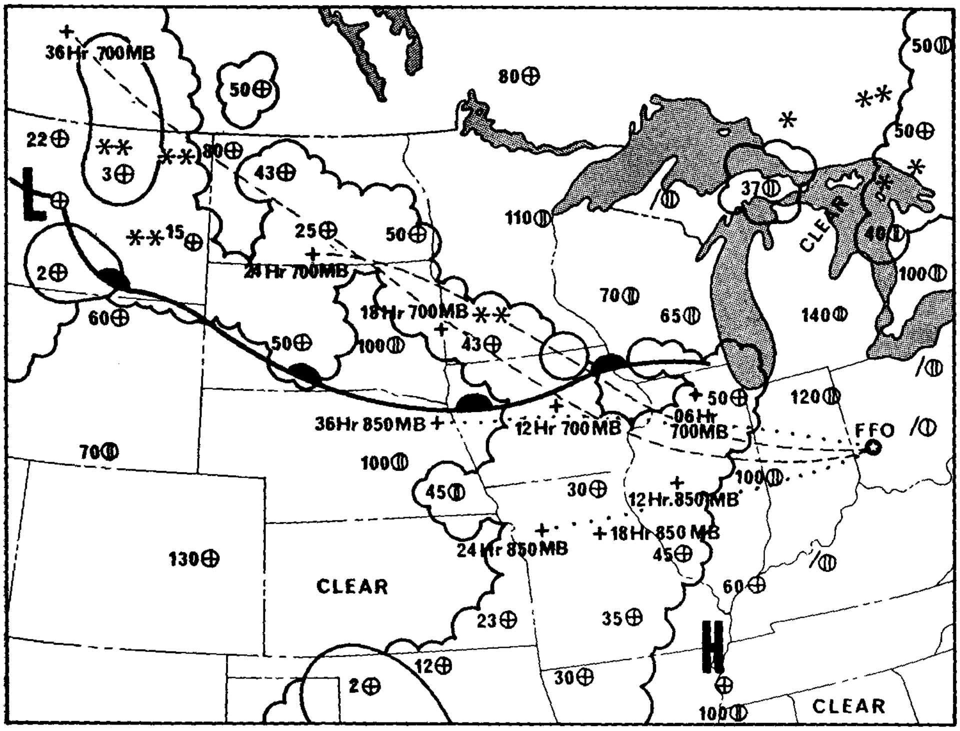

FIG. 4. Area nephanalysis and significant weather for 1300 GMT 19 February 1968. Scalloped lines enclose ceilings between 1000 and 5000 ft and visibilities ≥3 mi. Solid lines enclose ceilings <1000 ft and/or visibilities <3 mi. For clarity, only the 24- and 36-hr 850- (dots) and 700-mb (dashes) trajectories are shown. Crosses locate the initial points of other 850- and 700-mb trajectories.

TABLE 8. Forecast trajectory data for FFO, data base time (DT) 1200 GMT 19 February 1968.

Trajectory valid time	Initial trajectory coordinates		Initial pressure (mb)	Forecast pressure (mb)	Δp (mb)	Forecast		Forecast $T-T_d$ (°C)
	Lat(N)	Long(W)				T (°C)	T_d (°C)	
DT+06 hr	39.9	87.0	850	850	0	−9.0	−19.6	10.6
DT+12 hr	39.8	89.8	850	850	0	−6.8	−14.7	7.9
DT+18 hr	39.5	92.3	853	850	−3	−4.6	−9.9	5.3
DT+24 hr	39.4	94.3	857	850	−7	−2.2	−6.6	4.4
DT+36 hr	41.9	96.4	864	850	−14	−4.4	−9.7	5.3
DT+48 hr	49.3	97.3	845	850	+5	−15.9	−22.4	6.5
DT+06 hr	40.7	88.7	700	700	0	−13.5	−21.1	6.6
DT+12 hr	42.1	92.7	703	700	−3	−12.6	−12.9	0.3
DT+18 hr	44.2	96.7	704	700	−4	−12.6	−13.5	0.9
DT+24 hr	46.2	101.0	710	700	−10	−11.7	−13.1	1.4
DT+36 hr	51.2	109.6	710	700	−10	−13.1	−14.2	1.1
DT+48 hr	56.2	116.5	664	700	+36	−16.9	−25.3	8.4

based only on a correct occurrence or nonoccurrence forecast. In December and January, trajectory data correctly forecast 44 of 65 changes in the official TAFs. However, during November and February the trajectory-modified precipitation forecasts showed little or no skill. November's poor results are again attributed to the lack of experience in using trajectory data. Also, it was during this time that the objective precipitation rules were being formulated.

As mentioned earlier, the trajectory model encountered difficulty during the blocking regime of February when dry northerly flow influenced the central and eastern United States. Only 2 of 11 cases verified when the trajectory-modified TAF predicted precipitation. The dryness of the February regime is supported by the preponderance of correct "no-precipitation" forecasts. In 17 of 25 cases the trajectory-modified TAFs correctly forecast the absence of precipitation.

The 850-mb forecast temperatures were used to predict the form of precipitation reaching the surface according to the objective rules decribed in Section 3. The trajectory change verified in 15 of the 22 cases that were modified.

The four-month verification of the official precipitation forecasts was 83.1%. The corresponding trajectory verification was 84.4%, representing an improvement of 1.3% over the official forecasts. The monthly base verification varied in a small range from 82.1 to 83.6%. This was a surprisingly small variation when one considers that observed precipitation varied from 22% of the 6-hr periods in November and February to 37% of the 6-hr periods in January. Trajectory data improved the last two 6-hr periods of the base precipitation forecasts by 1.2%. This improvement appears significant considering that the Weather Bureau's 2.9% improvement from 1958 to 1966 (Porter and Roberts,

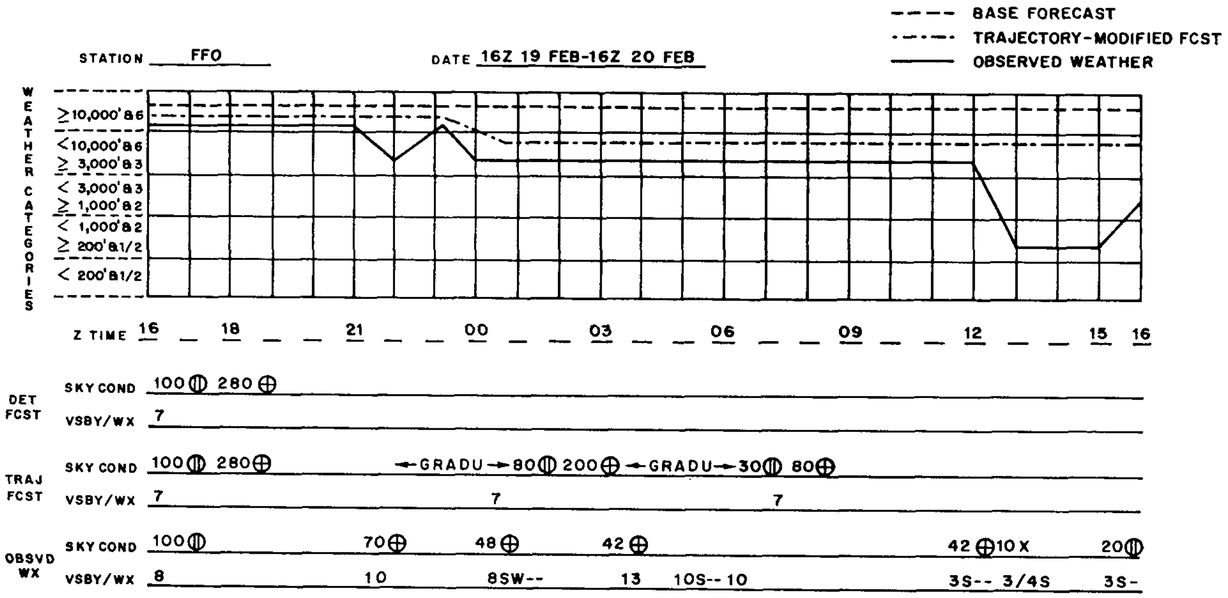

FIG. 5. FFO profile verification sheet for 19 February 1968. Format same as Fig. 2.

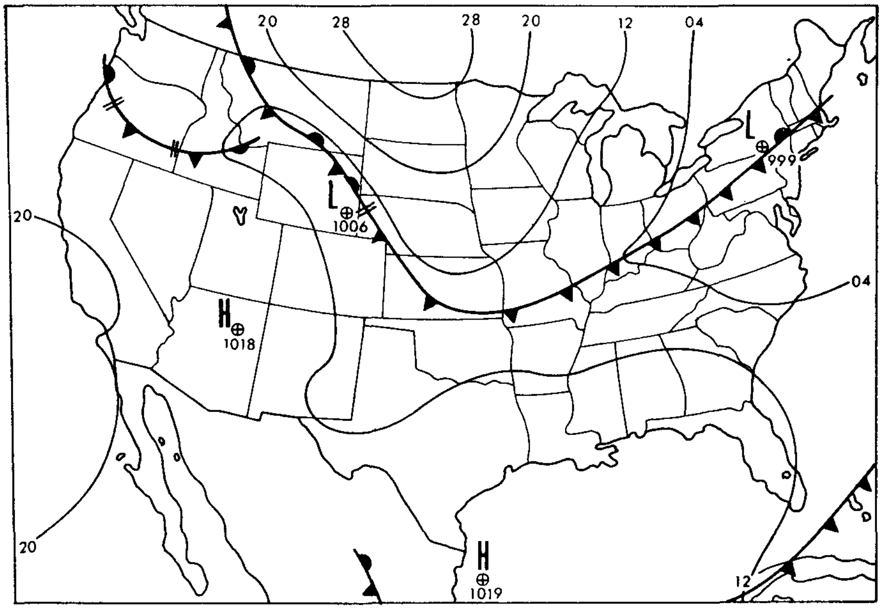

FIG. 6. Surface chart for 1200 GMT 20 February 1968.

1967) occurred during the period when rapid advances in numerical precipitation prediction were made by NMC.

6. Case study

A case study is presented to describe the method of evaluating the official TAFs and illustrate how the objective rules were applied. This case is a situation where forecast vertical motions were weak, but the advection of clouds and the forecast $T-T_d$ were sufficient to signal a change to lower conditions.

The case study was for FFO from 1600 GMT 19 February to 1600 GMT 20 February 1968. At 1200 GMT 19 February, high pressure affected the region of the eastern United States from Lake Erie south to the Gulf of Mexico (Fig. 3). A warm front extended westward from Wisconsin through northern Iowa and Nebraska into a surface low in Montana. A 300-mi wide band of clouds with bases between 3000 and 5000 ft extended north–south on the backside of the high from Texas through Okahoma, Missouri, Illinois and Iowa, and then westward along the warm front into Montana (Fig. 4). FFO reported a 10,000-ft ceiling at 1500 GMT 19 February.

The 24-hr TAF issued by FFO at 1600 GMT stated that the 10,000-ft ceiling would remain for the entire period (Fig. 5). Apparently, no change from the 1500 GMT observation was expected since the NMC surface prognoses for this period held the high-pressure center quasi-stationary over Tennessee. However, the forecast trajectory data indicated that definite changes would take place.

The forecast 850- and 700-mb trajectory data are shown in Table 8. The parcels expected to pass over the station at either 850 or 700 mb (column 5) are located initially on the 19 February 1200 GMT map at the latitude, longitude and pressure-height shown in columns 2, 3 and 4, respectively. The forecast pressure changes Δp along each parcel are listed in column 6. The times that the various parcels are expected to pass over the station are listed in Column 1, and the forecast T, T_d and $T-T_d$ are listed in columns 7, 8 and 9, respectively.

The forecast integrated vertical motions at 850 and 700 mb were weak for the entire period (rules 1 and 3); thus, advection of existing weather and forecast moisture were used to modify the FFO forecast (Table 8). The forecast 700-mb $T-T_d$ decreased from 6.6C for the 6-hr trajectory to 0.3C for the 12-hr trajectory. Likewise, the forecast 850-mb $T-T_d$ decreased from 7.9C for the 12-hr trajectory to 5.3C for the 18-hr trajectory. The initial point of the 6-hr 700-mb trajectory was on the edge of the cloud shield near Lake Michigan, while the initial point of the 12-hr 850-mb trajectory was on the edge of the cloud shield in Illinois (Fig. 4).

Advection supported a middle-cloud cover for the entire forecast period; however, sufficient moisture to support broken middle cloud was not forecast until approximately 1900 GMT (rule 2). The first 2 hr of the FFO forecast were not modified because of procedural rules. Again, following rule 2, the 10,000-ft ceiling was lowered to 8000 ft by 0100 GMT and subsequently to 3000 ft by 0600 GMT.

The observed ceiling remained at 10,000 ft until 2200 GMT when it dropped to 7000 ft, and subsequently lowered to 4200 ft by 0400 GMT and 1000 ft in snow by 1300 GMT. Very light intermittent snow was first observed at 0100 GMT. Snow was not included in the

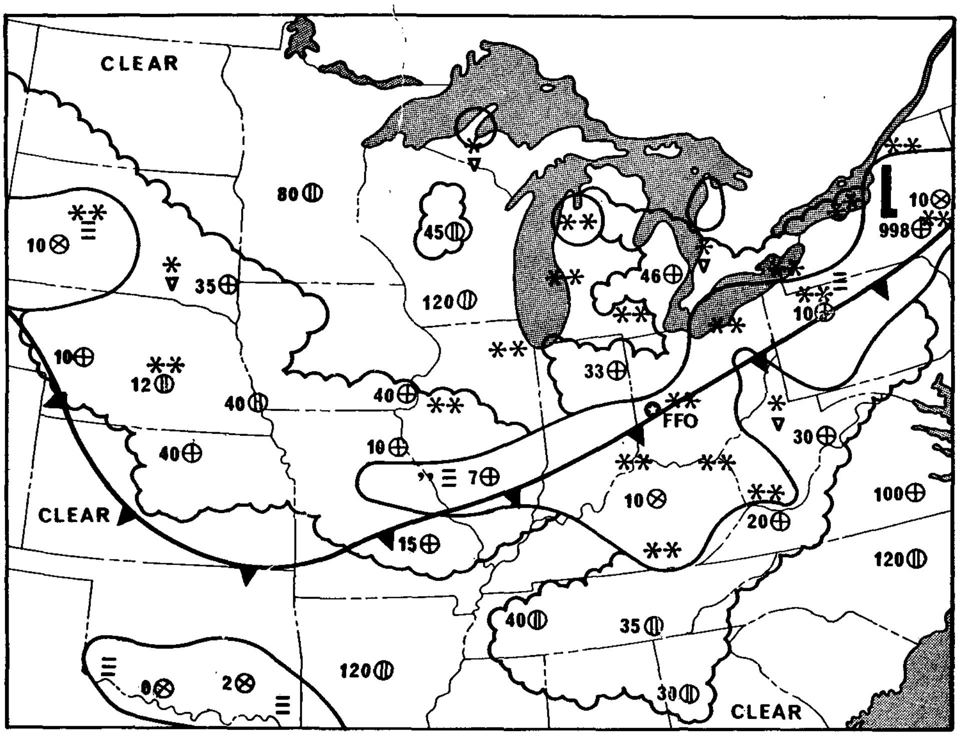

FIG. 7. Area nephanalysis and significant weather for 1300 GMT 20 February 1968. Nephanalysis symbols same as Fig. 4.

modified forecast because weak vertical motions were forecast for the period and upstream precipitation did not exist along the 850-mb trajectories (rule 3).

Fig. 6 shows that the warm front on the 1200 GMT 19 February surface analysis extended eastward and moved southward as a cold front on later charts. Fig. 7 shows the area nephanalysis for 1300 GMT 20 February. The cold front passed FFO about 1100 GMT 20 February. The trajectory data (Table 8) indicated a cold-frontal passage at 850 mb was expected prior to 0000 GMT 21 February (36-hr trajectory).

7. Conclusions

The results from the AWS trajectory evaluation were very encouraging. The purpose of the evaluation was to develop objective procedures for using trajectory data and to test these procedures to determine if their objective application improved the accuracy of the terminal forecasts. These procedures were developed early in the test and were followed throughout the test period. Their application produced an overall improvement in base ceiling and visibility forecast accuracy of 3.1%. This percentage is significant when compared to the small percentage improvements in AWS terminal weather forecasting during the past decade.

During the test period, the trajectory data were used to modify 19% of November's total forecast hours, 17% of December's, and 14% of January and February's. These trends indicate that trajectory forecasts became more refined as the test proceeded. This small percentage of modified TAFs improved the overall verification of ceiling and visibility categories by 3.1%.

In December and January, trajectory data correctly forecast 44 of 65 changes in the precipitation forecasts. Also, the 850-mb trajectory-forecast temperatures were used to predict correctly in 15 of 22 modified TAFs the form of precipitation (frozen or unfrozen) reaching the surface.

Although evidence in the literature indicates that the kinematic trajectory may not be the best estimate of the parcel's path (Danielsen, 1961; Djuric, 1961), the paper describes a good measure of success that was achieved by the use of a kinematic model applied above the region of most interest. Therefore, the future of trajectory forecasting looks particularly bright since a well-proven primitive-equation model soon will be introduced at AFGWC. This model will provide data to compute trajectories below 850 mb—the region where weather is most pertinent to USAF aerial operations. Current AWS interest in the development of an isentropic trajectory model and future developments in numerical weather prediction will provide products which should further improve terminal forecast accuracy.

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REFERENCES

Barnum, Dale C., 1966: Comparison of the temperature forecastability of the trajectory and six-level models. Unpubl. Rept., Aerospace Sciences, Hq AWS, Scott AFB, Ill.

Danielsen, Edwin F., 1961: Trajectories: isobaric, isentropic, and actual. *J. Meteor.*, **18**, 479–486.

——, 1966: Research in four-dimensional diagnosis of cyclonic storm cloud systems. Sci. Rept. No. 1, Contract No. AF19 (628)-4762, Pennsylvania State University, 53 pp.

Djuric, Dusan, 1961: On the accuracy of air trajectory computations. *J. Meteor.*, **18**, 597–605.

Donaldson, S. J., and R. J. Shafer, 1966: Some new approaches to probability and pattern methods for forecasting snow storms in the eastern United States. Meteor. Dept., Eastern Air Lines, Inc., 50 pp.

Edson, Herbert, 1966: Numerical cloud prediction. AWS Tech. Rept. 188, Hq AWS, Scott AFB, Ill., 135–143.

Fletcher, Robert D., 1956: Two outstanding problems of modern meteorology. *Bull. Amer. Meteor. Soc.*, **37**, 473–476.

Hanser, J., and A. H. Thompson, 1965: Vertical motion calculations and satellite cloud observations over the western and central United States. *J. Appl. Meteor.*, **4**, 18–30.

Kuhnsman, Donald, 1967: Verification of dew-point forecasts against selected raob stations. Unpubl. Rept., Aerospace Sciences, Hq AWS, Scott AFB, Ill.

Martin, D. E., 1966: Air Weather Service applications of numerical techniques to forecasting. *Adv. Numerical Weather Prediction, 1965–66 Seminar Series*, Travelers Research Center, Inc., 40–47.

Nagle, R. E., James R. Clark and Manfred M. Holl, 1966: Tests of the diagnostic-cycle routine in the interpretations of layer-cloud evolutions. *Mon. Wea. Rev.*, **94**, 55–66.

Porter, J. M., and C. F. Roberts, 1967: Recent trends in the accuracy and quality of Weather Bureau forecasting service. Wea. Bur. Tech. Memo. FSCT-8, Notes to Forecasters No. 8, Weather Analysis and Prediction Branch, Silver Spring, Md., 14 pp.

Posey, Julian W., 1968: The weather and circulation of February 1968. *Mon. Wea. Rev.*, **96**, 330–336.

Rogers, William C., and Paul E. Sherr, 1967: A study of dynamical relationships between cloud patterns and extratropical cyclogenesis. Final Rept., Contract No. E-47-67-(N), Allied Research Associates, Inc., Concord, Mass., 74 pp.