Evaluation of the Atlantic City Mesonet for Short Range Prediction of Aviation Terminal Weather[1]

HERBERT D. ENTREKIN, JAMES W. WILSON AND KEITH D. HAGE[2]

The Travelers Research Corporation[3], Hartford, Conn.

(Manuscript received 10 March 1969, in revised form 3 June 1969)

ABSTRACT

Two years of mesoscale weather data collected from the Federal Aviation Administration's Atlantic City mesometeorological network (mesonet) were used for the development and testing of techniques for 15-, 30- and 60-min predictions of runway visual range, cloud-base height and wind. The primary purpose of this work was to evaluate the utility of the mesonet for improved prediction of aviation terminal weather.

The first year of mesonet data was used for development work. Studies included preliminary development and testing of a prediction model based on advection; and, using detailed data analyses and a numerical-physical boundary-layer model, studies of methods for predicting changes due to non-advective processes.

The second year of mesonet data was used as independent data for testing six forecast techniques. Of the six techniques tested, three did not utilize mesonet data and were used for control purposes. The control forecasts were prepared from persistence, from trend, and by experienced U. S. Weather Bureau terminal weather forecasters. The forecasts based on mesonet data were prepared by a simple advection model which used low-level winds, by The Travelers Research Corporation (TRC) meteorologists and by U. S. Weather Bureau terminal weather forecasters.

The mesonet evaluation was made by comparing results from techniques that used mesonet data with those that did not use mesonet data. The results showed, in general, that none of the techniques that used mesonet data provided forecasts significantly better than those provided by persistence. It is therefore concluded, using the forecast methods evaluated, that the mesoscale data provided from the Atlantic City mesonet are not adequate for providing significantly improved short-range terminal weather forecasts.

There were three weather situations in which forecasts significantly better than persistence were obtained by TRC meteorologists. These forecasts were made by using a combination of mesonet and weather radar data. These special situations were 1) visual range restricted by snow, 2) dense fog accreted by rain, and 3) wind shift lines identified by radar or surface wind reports.

The general failure of the techniques that used mesonet data to provide better forecasts is attributed to the following: low-level winds alone are frequently not adequate for estimating the movement of the fields of cloud-base height and visual range; the number and arrangement of mesonet stations is not adequate for describing these fields or for determining their movement by analysis; and the techniques are not capable, in general, of predicting changes due to formation or dissipation.

1. Introduction

One of the basic requirements of aviation meteorology is accurate and timely short-period predictions of terminal weather conditions. This requirement, which has become increasingly important in the past few years because of tremendous expansion both in private and commercial air travel, and in the use of high-speed aircraft, is part of a general requirement for improvements in airport acceptance rates, terminal air space utilization, and safety. Despite remarkable improvements in airfield lighting, guidance systems, and traffic control procedures in recent years, airports continue to be closed at times because of weather; and delays, directly or indirectly attributable to weather, occur even with above minimum conditions.

It has been proposed by many meteorologists familiar with the short-range forecast problem that improved terminal weather forecasts could be obtained if more frequently cycled observations were available from a finer grid than that of the standard surface synoptic network. In order to examine this concept, the Federal Aviation Administration (FAA) installed an experimental network of 13 automatic weather observing stations (mesonet) around the National Aviation Facilities Experimental Center (NAFEC) at Atlantic City, N. J. The resulting mesonet configuration is shown in Fig. 1.

During the period 1 November 1965 to 31 October 1967, the FAA systematically collected weather data by episode from their Atlantic City (ACY) mesonet for

[1] This study was sponsored by the Systems Research and Development Service of the Federal Aviation Administration under Contract FA66WA-1536. This paper is a condensation of an earlier report by Entrekin et al. (1968).

[2] Present affiliation: The University of Alberta, Edmonton, Canada.

[3] Formerly, The Travelers Research Center, Inc.

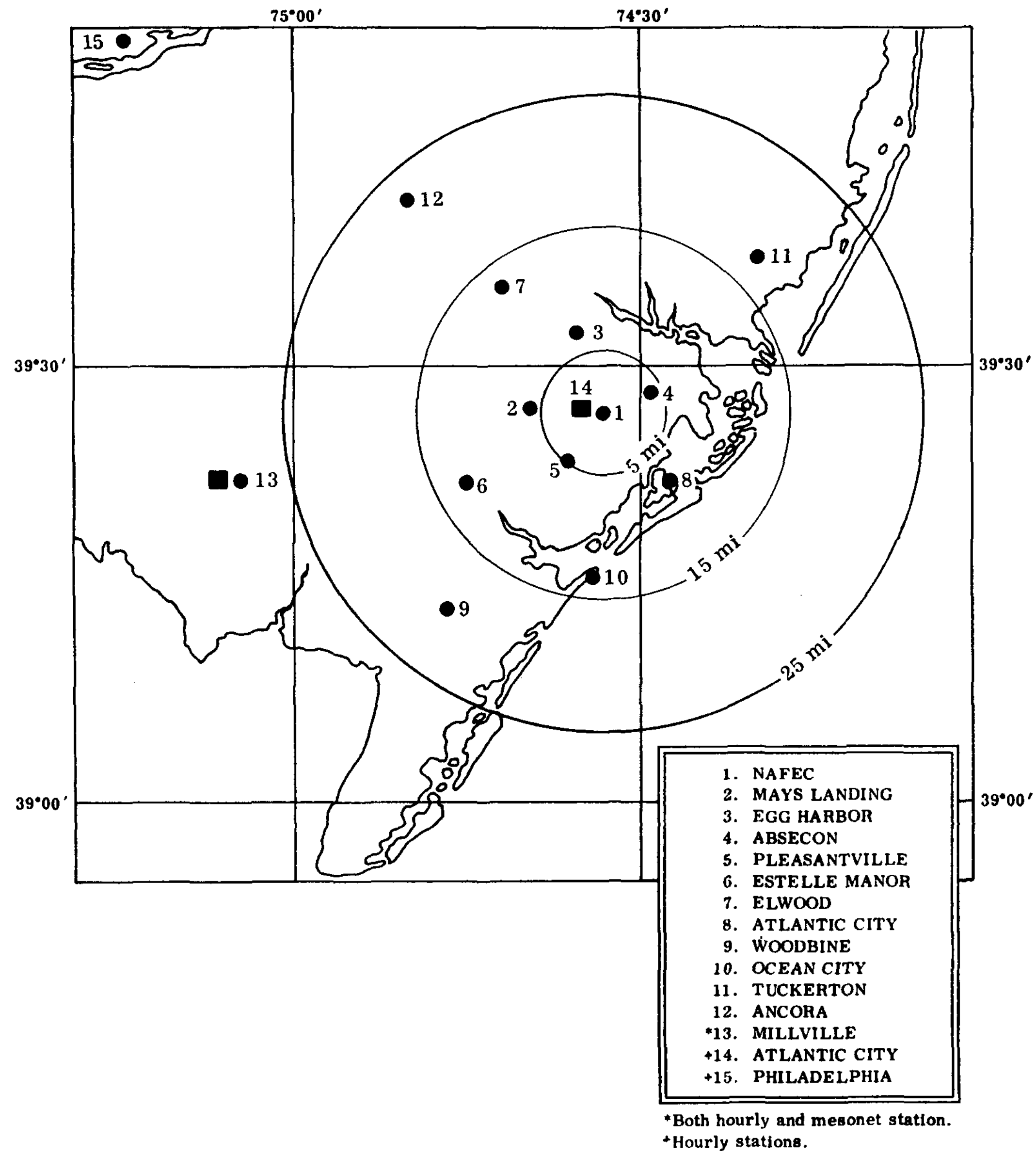

FIG. 1. Atlantic City mesonet station configuration.

detected or forecast occurrences of fog, low cloud or precipitation. The primary purposes of these collections were 1) to serve as dependent and independent data samples for the development and testing of techniques for 15-, 30- and 60-min predictions of runway visual range, cloud-base height and wind, and 2) on the basis of the test results, to evaluate the utility of the Atlantic City mesonet for improved prediction of aviation terminal weather.

The first year of mesonet data was used basically for development purposes, with primary emphasis being placed on runway visual range (RVR). Using these data, preliminary tests were made with a model based solely on advection, for predictions of per cent transmittance and cloud-base height. In addition, a numerical-physical boundary-layer model and detailed data analyses were used in studies of methods for predicting changes due to non-advective processes.

The second year of mesonet data was used as independent data for testing six forecast techniques. Of the six techniques tested, three did not utilize mesonet data and were used for control purposes. The control forecasts were 1) persistence, 2) extrapolation of past trends, and 3) subjective forecasts prepared by experienced U. S. Weather Bureau terminal weather forecasters. The forecasts based on mesonet data were prepared by a simple advection model which used low-level winds, by The Travelers Research Corporation (TRC) meteorologists, and by U. S. Weather Bureau terminal weather forecasters.

The purpose of this report is to point out some of the more interesting findings of the preliminary test and development studies and to present results of the prediction techniques tested with the second year of mesonet data.

2. Mesonet data

In general, observations of atmospheric transmittance, cloud-base height, temperature, dew-point temperature, wind speed and direction, occurrence or nonoccurrence of precipitation, and precipitation rate were available (in digital form on paper tape) from each of the 13 mesonet stations at 24-sec intervals. Exceptions to this were: cloud-base height observations were available every 12 sec; one or more stations usually were inoperative during each data collection; and no data were available from mesonet station 8 after 31 May 1966 or from mesonet station 10 after 3 April 1967. In addition to the above observations, analog records of pressure were available from about 5–7 stations for each data collection; soil temperature was available at depths of 1, 10 and 20 cm from stations 2 and 8; radiation measurements were available from stations 1 and 2; one or more special radiosonde soundings taken at ACY were usually available for each data collection; and photographs of the PPI radar scope of the U. S. Weather Bureau WSR-57 at ACY were available at approximately 15-min intervals for most mesonet collections. The PPI photographs were taken at 0° elevation using 6-db gain steps.

The number of development data samples collected during the first year of operation (1 November 1965 to 31 October 1966) was 66. The length of these samples ranged from 2 to 71 hr. The number of independent data samples collected during the second year (1 November 1966 to 31 October 1967) was 71; these samples varied in length from 2 to 52 hr.

For the purpose of testing the prediction techniques, predictand values were extracted from the data at 15-min intervals. Each predictand value for runway visual range, at light intensity setting 5 (RVR-LS5), was derived from the arithmetic mean of two consecutive 24-sec transmittance readings. Predictand values of cloud-base height were derived from the arithmetic mean of four consecutive 12-sec rotating-beam ceilometer (RBC) readings. Predictand values of wind speed and direction were resolved from arithmetic mean values of 10 consecutive 24-sec u and v wind component readings.

3. Preliminary test and development studies

The primary purposes of the preliminary studies were 1) to test the applicability of a simple advection model for predicting changes in transmittance and cloud-base height; and 2) to develop methods capable of predicting changes in these variables due to non-advective processes.

In relation to 1) 15-, 30-, and 60-min predictions of per cent transmittance and cloud-base height were made at 15-min intervals for mesonet station 1, for development data samples containing relatively low ($\leq 40\%$) and variable values of transmittance (16 cases), or low (≤ 1500 ft) values of cloud-base height (13 cases).

The results of the cloud-base height forecasts made with the advection model were "inconclusive" because predictor station cloud-base height data were frequently missing, and frequently, very high frequency variability was artificially introduced into the cloud-base height data. The latter occurred because the rotating-beam ceilometer (RBC) is not capable of discriminating between very low clouds (≤ 200 ft) or no cloud, especially during obscuration conditions. Also, intermittent observations of cloud-base height at the predictor and predictand stations, due to scattered or broken cloud conditions, caused discontinuities that could not be handled adequately by the prediction model tested. Because of these difficulties with the RBC data, most of the development program was geared toward methods for improving forecasts of transmittance (visual range).

For predictions of transmittance, the test results showed (Entrekin and Wilson, 1967), in general, that the accuracy of the forecasts based on advection were similar to those obtained by persistence, and that neither technique made consistently better forecasts. However, when the data samples (excluding radiation-type fogs) were separated for the "onset" and "ending" time periods, the forecasts based on advection were consistently better, by a small margin, than persistence forecasts for "onset" periods, and usually worse than persistence for "ending" periods.

Analyses of the fields of transmittance and their movements within the mesonet revealed some reasons why the advection method (later referred to as Basic Kinematic) did not provide better forecasts. The analyses showed that although the movement of the fields of transmittance for the fog onset were usually systematic in the approximate direction of the surface wind, the speed of movement usually did not agree well with the speed of the surface wind. Examples of these differences are presented in Table 1. The transmittance field movement in each case was determined by inspection of a series of transmittance maps analyzed at 4-min intervals.

With reference to Table 1, it is interesting to note that low-level (0–2000 ft) radiosonde wind data were available for collections M9-66, M18-66 and M19-66 near the approximate time the fog onsets occurred. For cases M9-66 and M19-66, the wind speed increased rapidly with height within the first few hundred feet of the atmosphere. By contrast, for case M18-66 the wind speed decreased with height for heights up to 1000 ft. This suggests that the speed of movement of the trans-

TABLE 1. Comparison of the movement of the transmittance field with the surface wind during the onset of low transmittance conditions.

Collection	Transmittance field movement (deg, kt)	ACY surface winds (deg, kt)
M1–66	090, 13	060, 8
M8–66	135, 16	120, 7
M9–66	135, 17	160, 7
M12–66	135, 5	220, 12
M15–66	120, 6	090, 15
M18–66	090, 6	070, 10
M19–66	200, 18	170, 10
M24–66	135, *	120, 9
M36–66	135, *	090, 7
M41–66	160, *	180, 5
M57–66	†	330, 5

* Speed erratic.
† No systematic movement.

mittance field at the surface may be better related to wind speeds at heights of about 500–1000 ft than to surface wind speeds. Unfortunately, low-level sounding data were not available at appropriate times for additional case studies.

In addition to the difficulties mentioned above, considerable change in fog density was noted in some cases as the fog moved between mesonet stations. An example of this is illustrated in Fig. 2 for fog advection from the east, where time-series curves of per cent transmittance for mesonet stations 1, 2 and 4 are shown for mesonet collection M15-66. Advection has been removed from Fig. 2 by time shifting the traces to correspond to the time required for the fog to advect to station 2. It is evident from Fig. 2 that the fog thinned considerably as it moved from stations 4 to 1 to 2. This thinning was typical when fog moved inland with onshore flow.

In 5 of 11 cases (excluding radiation fogs) the ending of low transmittance conditions occurred in coincidence with the forward edge of an advancing rain area. In each case, the apparent movement of the transmittance field was associated with the speed and direction of movement of the rain area. The corresponding increase in transmittance at the stations affected was attributed to the accretion process, i.e., the collision and coalescence of raindrops with the relatively smaller fog droplets (see Fig. 3).

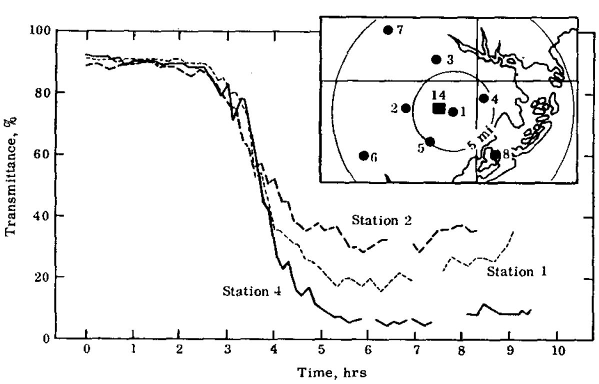

FIG. 2. Example of modification in the transmittance field as it advects from stations 4 to 1 to 2.

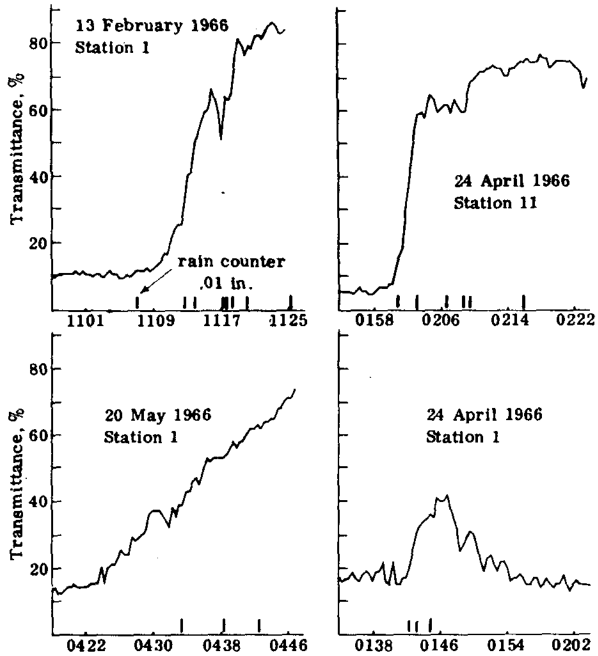

FIG. 3. Time series records of transmittance and rain counts (0.01 inch) showing the increase in transmittance with the onset of measurable rain.

In order to determine if the accretion concept could be worked into a useful forecast tool, the frequency with which rain falling into fog resulted in a increase in transmittance was summarized using 24-sec data from all mesonet stations. Care was taken not to include incidents in which heavy rain was the obscuring phenomenon. The results, which are based on 595 individual occurrences, are presented in Table 2.

Since the results of Table 2 indicated a positive relationship between rainfall rate and increasing transmittance, especially for rainfall rates >0.12 inch hr^{-1} and low initial values of transmittance, the average rate of increase in transmittance as a function of rainfall rate and initial transmittance was determined. The results are shown in Table 3. Table 3 indicates that useful forecasts of RVR may be possible in accretion situations, providing accurate forecasts of the occurrence and intensity of rain can be made.

TABLE 2. Percentage of cases in which transmittance increased during the time 0.01 inch of rain accumulated as a function of initial transmittance and rainfall rate.

Initial transmittance (per cent)	Rainfall rate (inches hr^{-1}) 0.02–0.12	>0.12
0–29	77	94
30–49	75	82
50–69	61	58

TABLE 3. Average rate of increase in transmittance (per cent min^{-1}) as a function of rainfall rate and initial transmittance

Initial transmittance (per cent)	Rainfall rate (inches hr^{-1}) 0.020–0.039	0.040–0.119	0.120–0.600	>0.60
0–29	0.9(8)*	1.1(23)	3.9(32)	14.2(4)
30–49	0.6(26)	0.7(30)	2.4(55)	9.7(17)
50–69	0.0(36)	0.2(103)	0.6(173)	3.0(88)

* Number of cases.

Five of the 16 development data samples tested for predictions of per cent transmittance were classified as radiation-type fogs. In addition to these five cases, eight additional cases[4] collected from the Atlantic City mesonet prior to 1 November 1965 were used for investigation of the radiation-fog prediction problem. It was found that about 50% of the variance in radiation fog ending times was accounted for by differences in sunrise time. In all 13 cases, dissipation of the fog began between 30 and 116 min after sunrise. The mean value was 73 min and the standard deviation 29 min. In all cases, transmittance $\geq 70\%$ within 30 min after dissipation began. More detailed resolution of fog ending times may have been possible had vertical profiles of temperature and moisture been available. Nevertheless, additional tests indicated that these statistics were potentially useful for improving 30- and 60-min predictions of radiation fog ending times. It was also found that mean values of transmittance derived from the inner ring of mesonet stations (stations 2, 3, 4 and 5) were potentially useful for improving 60-min predictions of per cent transmittance for radiation fog onset times. Further details of these radiation fog studies are given by Entrekin *et al.* (1968).

A numerical-physical boundary-layer model developed by Pandolfo *et al.* (1965) was also considered as a potential source for information that might be helpful in developing methods capable of predicting changes due to non-advective processes. This model, following some modifications, was applied to four cases selected from the development data collections. Results from the four cases indicated that the numerical-physical model was capable of simulating changes in fog and low clouds. It was also evident, however, that the model lacked the refinement necessary to provide the information required for accurate short-period predictions of visual range and cloud-base height. Details of this model and the results of tests made with the mesonet data are given by Chu (1967).

As indicated at the beginning of this section, the purpose of these early studies was to develop methods capable of improving short-range terminal weather forecasts. However, only some of the methods considered provided results sufficiently encouraging to warrant further testing. Thus, on the basis of these preliminary studies, all predictive features developed that showed promise for providing improved terminal weather forecasts were implemented into a single prediction model named "Modified Kinematic." A brief description of this model and the other prediction techniques tested using independent data are provided in Section 4.

[4] These radiation fog cases were collected during the mesonet nstallation and check-out period.

4. Description of forecast techniques tested using independent data

Six forecast techniques were tested using the Atlantic City independent mesonet data. The techniques were named: Basic Kinematic, Modified Kinematic, Manual 2, Manual 1, Trend and Persistence. Of these techniques, the latter three did not utilize mesonet data and were used for control purposes. For all techniques, the forecasts were prepared for mesonet station 1 (the central station) at 15-min intervals and for 15-, 30- and 60-min forecast periods. A brief description of each technique and the forecasts prepared with each follow.

a. Basic Kinematic

The term Basic Kinematic identifies the simple advection model used for preliminary tests with the development data sample. This technique was included in the test because earlier studies using runway transmissometer and wind data had shown positive indications of quasi-conservative transmittance pattern movement for time periods of up to 30 min (Hage and Entrekin, 1965).

The Basic Kinematic technique was limited to the preparation of forecasts of RVR-LS5[5] and cloud-base height, and included the following features. The surface winds recorded at mesonet station 1 were used to advect the fields of transmittance for predictions of RVR. Translation vectors specified for cloud-base height were obtained from special radiosonde soundings taken at ACY or from conventional soundings taken at the John F. Kennedy International Airport (JFK). For cloud-base height, wind vectors were specified from levels corresponding to the height of the cloud base.

b. Modified Kinematic

The results of the preliminary test and development studies were used as the basis for formulating the Modified Kinematic prediction technique. For this technique, forecasts of RVR, cloud-base height and wind were prepared. These forecasts were derived primarily from manual analyses of the mesonet, synoptic and radar data.

For wind, persistence was used as the forecast unless an approaching wind shift line was observed.

[5] Throughout the remainder of this report, RVR will be used to mean RVR-LS5 (runway visual range at light intensity setting 5).

For cloud-base height, persistence was used as the forecast except when movement of the cloud height field was observed. This movement was determined primarily by visual inspection of hand-analyzed mesonet data maps.

For RVR, persistence was used as the forecast unless 1) a movement of the transmittance field was observed (see cloud-base height above); 2) snow or heavy rain was expected to restrict visibility; 3) thinning of dense fog by accretion was anticipated; or 4) the onset or ending of radiation fog was expected.

For snow situations the RVR forecasts were based on hand-analyzed transmittance fields prepared from transmissometer and radar echo intensity data. The analyzed fields were then advected with the observed motion of the radar echoes.

For situations when it was suspected that accretion by rain droplets might thin dense fog, a forecast of the onset, duration and intensity of the rain was prepared using radar echo movement and intensity data. This forecast was then used as the basis for predicting changes in RVR caused by accretion, using relationships obtained between rainfall rate and the rate of increase in transmittance from studies made with the development data sample.

For situations when the onset of radiation fog was expected, nonpersistence forecasts were made only for the 60-min forecast period. Mean values of transmittance obtained from surrounding stations (stations 2, 3 4 and 5) were used for these forecasts.

When radiation fog was expected to dissipate near sunrise, nonpersistence forecasts were made only for the 30- and 60-min time periods. The procedure used assumed that radiation fog would begin dissipating 73 min after sunrise, unless the fog dissipated earlier, and that RVR would exceed 4000 ft within 30 min after dissipation began.

Detailed procedures and rationale for preparing Modified Kinematic RVR forecasts for the situations noted above were previously described by Wilson and Entrekin (1967).

c. *Manual 1 and Manual 2*

For each of the forecast techniques, Manual 1 and Manual 2, predictions of RVR, cloud-base height, wind speed and wind direction were prepared by U. S. Weather Bureau forecasters experienced in preparing aviation terminal weather forecasts. The U. S. Weather Bureau forecasters were detailed from the New York, Boston and Washington, D. C., Flight Advisory Weather Service (FAWS) Centers to Atlantic City for tours of approximately one month each. Manual forecasts were prepared only for the first seven months of the independent data sample (November 1966 to May 1967).

For the Manual 1 technique, the forecasters were provided with information usually available in a standard forecast environment, plus weather observations from mesonet station 1. These forecasts were prepared in real time.

For Manual 2, the standard weather information plus all mesonet data were made available to the forecasters. The mesonet data included computer data dumps of the raw mesonet data (24-sec messages) from all mesonet stations, computer generated 4- and 32-min mean values of mesonet data displayed in map arrays at 4- and 32-min intervals, special ACY radiosonde sounding data, net radiation measurements from mesonet station 2 beginning in January 1967, and total incoming radiation measurements from ACY. The Manual 2 forecasts were made in simulated real time. For all Manual type forecasts, access to present and past data was limited to the times specified in detail in the Test and Evaluation Plan prepared by The Travelers Research Center (1966). For additional details of the Manual techniques, the reader is referred to the report by Lefkowitz and McLaughlin (1967).

d. *Trend*

Trend forecasts of RVR and cloud-base height were prepared by extrapolating past trends of these variables into the future. Only times series observations of the predictand variable at the predictand station were used. The method used to estimate the time rate of change of each variable involved the use of triangular filter functions for smoothing past data. The data sample lengths used to obtain the trend estimates for the 15-, 30- and 60-min forecast periods were about 37, 64 and 136 min, respectively. Additional details of the Trend technique used for tests described in this report are given by Entrekin *et al.* (1968).

e. *Persistence*

Persistence forecasts were prepared for the variables RVR, cloud-base height, wind speed and wind direction for 15-, 30- and 60-min periods. The forecasts were obtained simply by projecting the latest observed value of each variable in time.

5. The independent data sample

During the period 1 November 1966–31 October 1967, discrete collections of mesonet data were made for detected or forecast occurrences of fog, low-cloud or precipitation. These samples (totaling 71 and collectively called the independent data sample) were used for independent tests of the forecast techniques described in Section 4 for predicting 15-, 30- and 60-min changes in RVR, cloud-base height and wind. The length of individual data samples ranged from about 2 to 52 hr.

According to the station 1 mesonet data, 49 of the 71 collections contained low values of either RVR or cloud-base height. Of the 49 collections, 19 contained extended periods of low RVR (≤4000 ft). Based on the weather phenomenon causing the restriction to visibility, six were classified as snow, one as heavy rain showers, eight as fog, and four as radiation fog. Thirty-eight of the 49 cases contained extended periods of low cloud (≤900 ft).

6. Forecast results

Evaluation of each forecast technique was based primarily on skill scores computed from contingency tables of observed and forecast categories of each variable. In most instances, the skill scores for each technique were computed from contingency tables representing the sum of all forecasts made for the individual data samples. In all instances, the skill score was computed relative to persistence. Correct forecasts were defined to be those observed in the same category as predicted.

The approximate number of forecasts prepared for each variable by each technique is as follows: Manual 1 (467), Manual 2 (881), Trend (2222), Basic Kinematic (3506), Modified Kinematic (3521), and Persistence (3505). Reasons for the major differences in the number of forecasts prepared by each technique are given by Entrekin *et al.* (1968).

a. Runway visual range

Evaluation of the RVR forecasts was based upon skill scores computed from contingency tables where the forecast and observed values were grouped into five categories: ≤1200 ft, 1300–1600 ft, 1700–2600 ft and ≥4000 ft. All available forecasts for each technique were used, the resulting scores being presented in Table 4.

In Table 4 it is not technically proper to compare techniques, because the forecasts were not made for equivalent data samples by each technique. For example, only 467 forecasts were made for the Manual 1 technique, compared to 881 for the Manual 2 technique. The primary purpose of Table 4 is to provide a comparison of each technique with persistence. A negative score indicates that persistence was the better forecast technique, while a positive score indicates that the comparative technique provided the better forecasts; a score of 1.0 would indicate perfect forecast accuracy.

Examination of Table 4 reveals that the forecasts provided by the various techniques usually were not as good as those provided by persistence. Exceptions to this were the Modified Kinematic technique which provided better forecasts than persistence for the 30- and 60-min forecast periods and the Manual 2 technique which provided better forecasts than persistence for the 60-min forecast period. It should be noted, however, that the improvement over persistence in each case was small.

TABLE 4. Skill scores* relative to persistence for 15-, 30- and 60-min forecasts of RVR.

Forecast period (min)	Manual 1	Manual 2	Trend	Basic Kinematic	Modified Kinematic
15	−0.11	−0.19	−0.35	−0.20	−0.03
30	0.00	−0.04	−0.15	−0.31	0.07
60	0.01	0.09	−0.14	−0.20	0.07

* See text for definition.

A paired t-test was used to determine the statistical significance of the performance of the Manual 2 technique in comparison to persistence for the 60-min forecasts (skill score=0.09). The results indicated that there was a 20% probability these results could have occurred by chance. Generally, a probability ≤5% is accepted as proof of significance.

In addition to evaluating the forecasts as above, that is, giving equal weight for all correct forecasts along the principal diagonal of the contingency table and zero weight for all remaining elements, a "weighted score" was defined and computed for RVR which gave more weight to correct forecasts at low RVR values than for high RVR values, and some weight for "close" forecasts. These scores were computed for the same techniques and data samples as those identified previously. The results showed essentially the same features as the skill scores presented in Table 4. Again, the best improvement over persistence was provided by the Modified Kinematic and Manual 2 techniques.

During the preparation of the Modified Kinematic forecasts, it was noted that persistence was used as the forecast ~90% of the time for each forecast period; however, it should be pointed out that the majority of persistence forecasts were made when RVR exceeded 4000 ft (the highest category). Of those occasions where RVR was observed to change during the forecast period from one category[6] to another, nonpersistence forecasts were made approximately 50% of the time. It is interesting to note that for times when RVR changed categories during the forecast interval, snow, radiation fog, and accretion of fog by rain accounted for approximately 20, 20 and 3% of the occurrences, respectively. The remaining 57% were associated with advective or non-advective changes in fog density.

Each nonpersistence forecast made was stratified according to the following weather types: snow, accretion, radiation fog onset, radiation fog ending, and fog advection. The forecast accuracy for each was determined and the results are presented in Table 5.

The ability of the Modified Kinematic technique to produce forecasts better than persistence for the snow and fog accretion situations is quite encouraging since

[6] The RVR limits for each category were the same as those used throughout this section. For the total data sample, RVR values changed from one category to another during the forecast period 5% and 9% of the time for the 15- and 60-min forecast periods, respectively.

TABLE 5. Comparison of 15-, 30-, and 60-min RVR forecasts by the Modified Kinematic and Persistence techniques for periods when nonpersistence forecasts were made for various weather types

Weather type	Number of forecasts	Per cent correct* Modified Kinematic	Persistence
	15-min forecasts		
Snow	153	77	74
Accretion	7	71	43
Fog advection	122	55	61
Total	282	67	67
	30-min forecasts		
Snow	154	71	63
Accretion	9	89	33
Radiation fog ending	10	40	10
Fog advection	137	51	56
Total	310	63	57
	60-min forecasts		
Snow	154	73	60
Accretion	12	92	25
Radiation fog ending	22	45	35
Radiation fog onset	20	45	45
Fog advection	134	45	46
Total	342	59	50

* A forecast was defined to be correct if it was observed in the same category as forecast.

the available radar data were far from ideal. That is, the mesonet stations were located primarily in the ground clutter of the radar, and the collection of radar data was periodically interrupted for Weather Bureau operations.

Although the Modified Kinematic technique showed improvement over persistence for forecasting the ending of radiation fog, the results were actually better than might be expected. The forecast procedure, which was based on the development data sample, assumed that radiation fog would begin dissipating 73 min after sunrise. However, for the test sample, the mean dissipation time after sunrise was 111 min, indicating that the forecasts dissipated the fog too early. Because of this difference some poor forecasts were made. However, in some instances these poor forecasts were not included in the evaluation because the mesonet was shut down temporarily to change paper tapes[7] precisely at the time the forecasts would have verified. Therefore, the Modified Kinematic forecasts for radiation fog endings were somewhat less accurate than indicated by the results of Table 5.

It is evident from Table 5 that the Modified Kinematic technique provided the poorest forecasts for the weather type labeled "fog advection." The failure of this method appears to be related to a combination of the following factors:

[7] Paper tapes are used to record the raw weather observations transmitted from each mesonet station.

1) The mesonet station spacing (~4–10 mi) was not of sufficient density to determine whether the movement suggested by analysis was systematic, or to determine the speed and direction of movement with sufficient accuracy.
2) Changes in the fog density caused by formation or dissipation were frequently large relative to those caused by advection.

Factor 1) was particularly significant during the most critical forecast periods (the onset or ending of low RVR) because the gradients in the transmittance fields in these situations are exceptionally large. The scarcity of stations was particularly critical for movement from easterly directions.

While a denser, more extensive network would enable more accurate identification of the initial transmittance field and better determination of its movement, it is not known if this would provide a significantly increased forecast accuracy. The reasons are that considerable formation or dissipation of fog frequently occurs within short time intervals, and the present techniques are not, in general, capable of predicting changes due to formation or dissipation. This problem is more pronounced within the Atlantic City mesonet because of its proximity to the ocean.

b. Cloud-base height

Evaluation of the cloud-base height forecasts was based upon skill scores computed from contingency tables where the forecast and observed values were grouped into the following categories: 100 ft, 200–400 ft, 500–900 ft, 1000–2000 ft and >2000 ft. Forecast and observed values of cloud-base height <100 ft were excluded from the evaluation because the rotating-beam ceilometer (RBC) is not capable of distinguishing between a very low cloud and no cloud, especially during periods of surface-based obscurations or during precipitation, such as snow, which greatly attenuates the RBC light. Except for this restriction, all available forecasts for each technique were used. The resulting skill scores are presented in Table 6.

As with Table 4 for the RVR forecasts, it is not technically correct to compare techniques since the same number of forecasts were not made with each technique. The purpose of Table 6 is to provide a comparison of each technique with persistence. The predominance of negative skill scores for all techniques indicates that

TABLE 6. Skill scores relative to persistence for 15-, 30- and 60-min forecasts of cloud-base height.

Forecast period (min)	Manual 1	Manual 2	Trend	Basic Kinematic	Modified Kinematic
15	−0.25	−0.20	−0.43	−0.23	−0.04
30	−0.29	−0.23	−0.32	−0.14	−0.04
60	−0.36	−0.21	−0.28	−0.05	0.01

persistence was the best forecast. The only exception was that a positive skill score for the 60-min forecast was provided by the Modified Kinematic technique. With the possible exception of the Basic Kinematic technique, all techniques compared less favorably to persistence for forecasts of cloud-base height than for RVR.

There appears to be several reasons why the Basic Kinematic technique did not provide better forecasts. First, clouds occasionally do not advect with the low-level winds. Second, the high frequency variability of cloud-base height, especially during broken or scattered cloud conditions, frequently obscures advection of any mesoscale changes. Third, on occasions the input wind at cloud-base height was probably not representative of current local winds. Whenever available, winds were obtained from radiosondes taken at ACY; however, it was necessary to use the New York radiosonde information (~100 mi away) roughly 75% of the time. Fourth, because of the sparsity of mesonet stations at certain ranges and directions, appropriate predictor information was frequently not available.

Of those occasions (about 6%) when the cloud-base height was observed to change during the forecast period from one category to another, nonpersistence forecasts for the Modified Kinematic technique were made only 5% of the time. This low percentage simply reflects that it was rarely possible to observe any movement from the analyzed cloud-height field.

Skill scores relative to persistence were computed for the nonpersistence forecasts of cloud-base height made by the Modified Kinematic technique. The results showed that persistence provided better forecasts for the 15- and 30-min forecast periods, and that the Modified Kinematic technique provided better forecasts for the 60-min period; the skill score was 0.16. The failure to improve upon persistence for the 15- and 30-min forecasts may be the result of difficulty in accurately determining the rate of movement of the cloud or the failure of the observed movement to persist throughout the forecast period. An equally likely reason may be that the high-frequency variability in cloud height during broken and scattered conditions is so large that it masks any larger scale advective changes that might occur in 15 or 30 min.

c. *Wind direction*

Only three techniques were used to prepare wind direction forecasts: Manual 1, Manual 2 and Modified Kinematic, the skill scores being presented in Table 7. When computing the skill scores, a forecast was defined as correct if it was within 20° of the observed direction. As with the skill scores for forecasts of RVR and cloud-base height, it is not correct to compare techniques since forecasts were not made for comparable time periods.

Table 7. Skill scores relative to persistence for 15-, 30- and 60-min forecasts of wind direction.

Forecast period (min)	Manual 1	Manual 2	Modified Kinematic
15	−0.78	−1.08	0.03
30	−0.53	−0.22	0.04
60	−0.26	−0.12	0.05

It is evident from Table 7 that only the Modified Kinematic technique produced positive scores. The improvement over persistence, however, was small.

The Modified Kinematic technique forecast persistence until a wind shift line could be identified and extrapolated. Observations from the U. S. Weather Bureau ACY radar and the mesonet stations showed during each of seven data collections that surface wind shift lines were associated with a line of precipitation echoes. These lines of echoes were often traceable by radar for several hours before they reached the predictand station, thus making possible accurate determination of the movement of the wind shift line. Between a quarter and a third of the nonpersistence forecasts made by the Modified Kinematic technique were based on these radar observations. The remainder of the nonpersistence forecasts were based on extrapolation of wind shift lines observed from synoptic and mesoscale analyses.

Nonpersistence forecasts were made for only 10–15% of the occasions when wind direction was observed to change by more than 20°. The average wind speed when nonpersistence forecasts were made was 8 kt. While there was no means to determine the proportionate number of wind direction changes $>20°$ that occurred with various wind speeds, a considerable number probably occurred in coincidence with very light winds (speeds$\leq$3 kt). Since direction changes that occur in light winds have a minimum effect on aircraft operations, the percentage of nonpersistence forecasts, made when winds were of significant operational interest, is probably greater than that indicated by the 10–15% figure.

Table 8 shows the skill scores relative to persistence for forecasts of wind direction at times nonpersistence forecasts were made by the Modified Kinematic technique. As in Table 7, a forecast was considered correct if it was within 20° of the observed.

From Table 8 it is clear that these Modified Kinematic wind forecasts were considerably better than those based on persistence.

d. *Wind speed*

Wind speed forecasts were made only for the Manual techniques. Forecast evaluation was based on contingency tables where the forecast and observed wind speeds were grouped into five categories: 0–5, 6–10,

TABLE 8. Skill scores relative to persistence for forecasts of wind direction by the Modified Kinematic technique at times non-persistence forecasts were made.

Forecast period (min)	Number of forecasts	Skill score
15	46	0.37
30	69	0.36
60	97	0.35

11–20, 21–35 and >35 kt. A forecast was defined as correct if it was observed in the same category as predicted. Skill scores computed relative to persistence for each technique showed that the forecasts by the Manual techniques were consistently less accurate than persistence forecasts. It is of interest to note that wind speed changed by more than 5 kt only 4% of the time during a 60-min time period.

6. Summary and conclusions

Concerning the forecast accuracy of the individual short-range prediction techniques, it was found that:

1) For cloud-base height, no other technique provided better forecasts than persistence.
2) For 15-min forecasts of RVR, no other technique provided better forecasts than persistence.
3) For 30-min forecasts of RVR, only the Modified Kinematic technique provided better forecasts than persistence. However, the improvement was small.
4) For 60-min forecasts of RVR, the Manual 2 and Modified Kinematic techniques provided better forecasts than persistence. The improvement, however, was small.
5) For two weather situations, visibility restrictions due to snow and the accretion of dense fog by rain, the Modified Kinematic technique provided better forecasts than persistence for all forecast periods. For the accretion situations, the improvement over persistence was considerable.
6) For wind speed, persistence was the best of three techniques tested.
7) For wind direction, the Modified Kinematic technique was the only technique that provided forecasts better than persistence. The improvement over persistence was considerable in instances when wind direction discontinuities could be located, either by synoptic, mesoscale, or weather radar information.

Based on the prediction techniques tested, the mesoscale data from the Atlantic City mesonet are generally inadequate for significantly improving short-range predictions of RVR, cloud-base height and wind. This is attributed to the following:

1) The speed and direction of movement of the fields of transmittance and cloud-base height frequently could not be estimated from low-level winds alone.
2) The present station spacing (~4–10 mi) within the mesonet is not of sufficient density to specify the initial fields of transmittance and cloud-base height, or to enable the speed and direction of movement of these fields to be accurately determined by analysis.
3) Because the spatial variability of RVR and cloud-base height is frequently large compared to the distance between mesonet stations, appropriate predictor data were frequently missing. This was especially true for directions to the east of mesonet station 1.
4) Changes in RVR and cloud-base height caused by formation or dissipation were frequently large relative to those caused by advection.
5) The techniques developed for predicting changes in RVR and cloud-base height, in general, were not capable of predicting changes caused by formation or dissipation.
6) The rotating-beam ceilometer is not adequate for measuring cloud-base heights ≤200 ft, especially during obscuration conditions.
7) The high frequency variability of cloud-base height, especially during scattered or broken cloud conditions, frequently obscures advection of any mesoscale changes.
8) The use of the Atlantic City U. S. Weather Bureau radar as a forecast tool was limited because most of the mesonet stations are located within the radar's ground clutter pattern.

On the basis of the above observations, it is concluded if short-range forecasts of RVR and cloud-base height are to be improved significantly, that the following are required. First, techniques must be developed that are capable of predicting changes due to formation and dissipation as well as due to advection. Second, the mesonet station configuration should contain stations sufficiently dense that the speed and direction of movement of features can be determined by objective analysis techniques. Third, the rotating-beam ceilometer should be modified to include the capability for measuring accurately low-cloud bases (bases ≤200 ft), and for measuring vertical visibility in obscurations such as fog and snow. Finally, frequent vertical soundings of air temperature, moisture, wind and liquid water content should be made in the lowest few hundred feet of the atmosphere.

Acknowledgments. The study would not have been possible without the high quality data provided by the ESSA-Weather Bureau team responsible for the operation and maintenance of the Weather Test Environment at the National Aviation Facilities Experimental Center in Atlantic City. Special thanks are due to Mr. M. Lefkowitz, Chief, Observations and Methods Branch (ESSA-Weather Bureau, NAFEC), to Mr. R. Irwin, FAA Project Manager at NAFEC, and to the ESSA-Weather Bureau Flight Advisory Weather Service

Center meteorologists who volunteered to serve as test forecasters.

Thanks are due also to Messrs. G. Wickham and G. B. Lassow of TRC for assistance in computer data processing and analysis and to P. J. Budaj of TRC for assistance in manual analysis and data processing.

REFERENCES

Chu, R. T., 1967: Diagnostic studies of fog and low cloud in the Atlantic City mesonetwork. Tech. Note (Paper A), Contract FA66WA-1536, The Travelers Research Center, Inc., 57 pp.

Entrekin, H. D., K. D. Hage, G. Wickham and J. W. Wilson, 1968: Specifications and descriptions of computer programs developed for the Atlantic City mesonetwork. Rept. prepared under Contract FA66WA-1536, The Travelers Research Center, Inc., 127 pp.

——, and J. W. Wilson, 1967: Test of a Kinematic Model for 15–60 minute forecasts of transmittance and low cloud-base height. Tech. Note, Contract FA66WA-1536, The Travelers Research Center, Inc., 40 pp.

——, —— and K. D. Hage, 1968: Evaluation of the Atlantic City mesonet for short-range prediction of aviation terminal weather. Final Rept. 7481–307, Contract FA66WA-1536, The Travelers Research Center, Inc., 116 pp.

Hage, K. D., and H. D. Entrekin, 1965: Further studies of space and time variations in atmospheric transmission along airport runways. Tech. Rept. 7417-143, Contract FA66WA-1192, The Travelers Research Center, Inc., 32 pp.

Lefkowitz, M., and D. McLaughlin, 1967: Test use of mesonet data in manual forecast preparation. Final Rept., Inter-Agency Agreement FAA67WAI-126, ESSA, Weather Bureau 21 pp.

Pandolfo, J. P., D. S. Cooley and M. Atwater, 1965: The development of a numerical prediction model for the planetary boundary layer. Final Rept. 7465-174, The Travelers Research Center, Inc., 147 pp.

The Travelers Research Center, Inc., 1966: Evaluation of the utility of the Atlantic City mesonetwork for the improvement of terminal weather information. Tech. Note—Test and evaluation plan, Contract FA66WA-1536, 28 pp.

Wilson, J. W., and H. D. Entrekin, 1967: Diagnostic studies of fog and low cloud in the Atlantic City mesonetwork. Tech. Note (Paper B), Contract FA66WA-1536, The Travelers Research Center, Inc., 27 pp.