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PREFACE

This report describes a method for forecasting low-level winds in the Terminal Environment in the 30 to 60 minute timeframe. Tests are performed using data from Lincoln Labs' Terminal Winds analysis system, run in Memphis, TN in the summer of 1994. Two gust front events (June 9 and June 21) are examined. Skill scores are calculated for each experiment and compared with persistence. Some preliminary conclusions and recommendations are then made.
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1. INTRODUCTION.

1.1. The Terminal Winds system.

Winds in the terminal area have a significant impact on airport operations and safety. Fuel optimal trajectories for aircraft descending from cruising altitude into the terminal airspace and proper vectoring of aircraft descending to the runway depend on aircraft headwind. Wake vortices generated by landing aircraft persist long enough to be hazardous only in certain meteorological conditions which depend, among other things, on the horizontal wind. Changing wind conditions at the airport often require changing which runways are used for landing and takeoff.

Low level winds also have an important effect on the generation and maintenance of severe convection. Since the late 1940’s it has been known that thunderstorms most often form in regions where low-level winds converge. An accurate analysis and forecast of the low-level wind field is therefore very useful for forecasting the development of severe thunderstorms.

Recently, Lincoln Labs/MIT has been developing a wind analysis system called ITWS Terminal Winds for the FAA. This system obtains wind information from a number of sources: a national scale forecast model, meteorological Doppler radars, commercial aircraft, and surface anemometers. The Terminal Winds analysis technique, which is called Optimal Estimation (OE), uses a minimum error variance method (least squares) and is closely related to both Optimal Interpolation and standard multiple Doppler methods.

1.2. Forecasting Terminal Winds.

The Terminal Winds system development has concentrated on an up-to-date analysis of the wind field. An accurate forecast of low-level winds also has value for many of the reasons mentioned above. In this report we describe and test a technique for short term prediction of winds in the Terminal area.

The forecasting methodology we have used is to initialize a small-scale numerical model with data from the Terminal Winds analysis system. Since a numerical forecast requires information about the temperature field, we use a technique called thermodynamic retrieval.
to derive this field from a time series of wind analyses. Once the model is initialized with wind and temperature fields, it can be integrated forward to produce forecasts of wind and temperature.

In this report, we first summarize the Terminal Winds analysis system and then describe the technique for wind prediction. We then describe tests of this system using data from the DemVal carried out in the summer of 1994 in Memphis.

2. THE TERMINAL WINDS ANALYSIS.

2.1. Overview.

The primary philosophy of the Terminal Winds analysis is that the national scale forecast models provides an overall picture of the winds in the terminal airspace although painted in very broad strokes. The terminal sensors are then used to fill in detail, and correct the broad scale picture. The corrections and added detail can only be provided in those regions with nearby data. What constitutes “nearby” depends on the spatial and temporal scale of the feature to be captured in the analysis. The refinement of the broad scale wind field is accomplished by averaging the model forecasts with current data. This allows the analysis to transition from regions with a large number of observations to regions with very few observations, or no observations at all, and enables the analysis to cope with unexpected changes in the availability of sensors.

To account for the different scales of wind features and the differing resolution of the information provided from the various sensors, the analysis employs a cascade-of-scales. This cascade-of-scales uses nested grids, with an analysis with a 2 km horizontal resolution and 5 minute update rate nested within an analysis with a 10 km horizontal resolution and 30 minute update rate, which in turn is nested within the MAPS forecast with a 60 km horizontal resolution and 180 minute update rate. All of the data sources are used in the 10 km analysis, and data are allowed to be as old as 90 minutes. Only the information from the Doppler radars and LLWAS are suitable for the 2 km analysis. This cascade-of-scales is appropriate for the scales to be captured in the analysis and provides a uniform level of refinement at each step of the cascade (as shown in Table 1). An additional benefit is that
the 10 km analysis acts as a stand in for the planned 10 km national forecast. When a 10 km national forecast becomes available, the 10 km ITWS analysis can be dropped.

TABLE 1. Scales of analysis for MAPS and Terminal Winds

<table>
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<tr>
<th></th>
<th>update rate</th>
<th>horizontal resolution</th>
<th>domain size</th>
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<tbody>
<tr>
<td>MAPS</td>
<td>180 min</td>
<td>60 km</td>
<td>national</td>
</tr>
<tr>
<td>Terminal Winds-above PBL</td>
<td>30 min</td>
<td>10 km</td>
<td>250x250 km</td>
</tr>
<tr>
<td>Terminal Winds-in PBL</td>
<td>5 min</td>
<td>2 km</td>
<td>120x120 km</td>
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An important goal is the minimization of the error of the analyzed wind field. To achieve this goal Terminal Winds uses a least squares technique. This technique is designed to jointly average both vector quantities and single component quantities. Previous state-of-the-art operational winds analysis systems have used statistical techniques to great advantage. However, none has the ability to analyze directly the data from Doppler radars. Terminal Winds provides a new capability which is important since increasing numbers of Doppler weather radars are being deployed.

The least squares accounts for the differing quality of the information available to Terminal Winds, as well as errors arising from data age and using data at locations removed from the location at which the data were collected (displacement error). The least squares also corrects for correlated errors. Highly correlated displacement errors arise frequently due to the nonuniform distribution of data from the Doppler radars. If these correlated errors are not accounted for, these data dominate the analysis to a greater degree than warranted by their information content.

2.2. Terminal Winds Interpolation Technique: Optimal Estimation.

The Terminal Winds analysis is dominated by Doppler radar data. In regions with coverage by two or more radars, the Terminal Winds system should provide winds with at least the quality of a traditional multiple Doppler analysis. The state-of-the-art analysis technique for non-Doppler meteorological data analysis is Optimal Interpolation (OI).
Optimal Interpolation is a statistical interpolation technique that under certain hypotheses gives an unbiased minimum variance estimate. We wish to build on the foundation laid down by both the multiple Doppler analysis and statistical interpolation techniques.

We have developed an unbiased minimum error variance technique that utilizes Doppler measurements directly. We call this technique Optimal Estimation (OE) to distinguish it from Optimal Interpolation. The initial focus is on analyzing horizontal wind data to a three dimensional grid, however, the method applies to other variables. The method is based on the Gauss-Markov theorem, and under suitable conditions gives an unbiased minimum error variance estimate of the horizontal winds. Optimal Estimation is an extension of both Optimal Interpolation and multiple Doppler analysis. It is the ease with which OE incorporates Doppler radar data that motivates its development.

OE has the following properties:

1. Dual Doppler quality winds are automatically provided in regions where dual Doppler is numerically stable.

2. Small gaps in dual Doppler radar coverage are filled to provide near dual Doppler quality winds in these gaps.

3. The analysis smoothly transitions between regions with data from differing numbers of Doppler radars.

Throughout this section we use the following notation conventions:

- $r$ denotes a radial wind component

- $u$ denotes an east wind component

- $v$ denotes a north wind component

- superscript $\alpha$ denotes an analyzed quantity

- superscript $b$ denotes a background quantity

- superscript $o$ denotes an observed quantity

- subscripts denote location, $o$ denoting an analysis location
In order to apply the Gauss-Markov theorem, we need to pose the problem in the form

\[ Ax = d, \quad \text{where} \]

\[ x = (u^a, v^a)^T, \quad \text{(superscript } T \text{ indicates transpose),} \]

and the data vector \( d = (u^b, v^b, u^o, v^o, ..., u^m, v^m, r^o, ..., r^n)^T \) contains the background estimate at the analysis location, and observations in a data window centered on the analysis location. The form of the matrix \( A \) depends on the type of data, vector and/or radial, to be analyzed. The Gauss-Markov theorem states that the linear minimum variance unbiased estimate of \((u^a, v^a)^T\) is given by

\[ (u^a, v^a)^T = (A^T C^{-1} A)^{-1} A^T C^{-1} d, \quad (2.2) \]

if each element of \( d \) is unbiased, and \( C \) is the error covariance matrix for the elements of \( d \). The error covariance of the solution is

\[ (A^T C^{-1} A)^{-1}. \quad (2.3) \]

The minimum data window covers a 3x3 grid point region, so frequently the data window contains several Doppler values. In the case of \( m \) vector observations, and \( n \) Doppler observations, equation 2.1 has the form:

\[
\begin{pmatrix}
1 & 0 & 1 & 0 & 1 & \cos \theta_1 & \sin \theta_1 & \vdots & \vdots & \cos \theta_n & \sin \theta_n \\
0 & 1 & 0 & 1 & \cos \theta_1 & \sin \theta_1 & \vdots & \vdots & \cos \theta_n & \sin \theta_n \\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
1 & 0 & 1 & 0 & 1 & \cos \theta_1 & \sin \theta_1 & \vdots & \vdots & \cos \theta_n & \sin \theta_n \\
\end{pmatrix}
\begin{pmatrix}
(u^a) \\
y^b \\
y^o \\
1 \\
0 \\
\vdots \\
\cos \theta_1 \\
\sin \theta_1 \\
\vdots \\
\cos \theta_n \\
\sin \theta_n \\
\end{pmatrix}
= 
\begin{pmatrix}
1 \\
0 \\
\vdots \\
0 \\
\vdots \\
\vdots \\
\vdots \\
\vdots \\
\cos \theta_1 \\
\sin \theta_1 \\
\vdots \\
\cos \theta_n \\
\sin \theta_n \\
\end{pmatrix}
\begin{pmatrix}
u^b \\
v^o \\
u^m \\
v^o \\
r^o \\
r^o \\
r^o \\
r^o \\
1 \\
0 \\
\vdots \\
\cos \theta_1 \\
\sin \theta_1 \\
\vdots \\
\cos \theta_n \\
\sin \theta_n \\
\end{pmatrix}.
In practice, $C$ is not known and must be estimated. There are two types of errors to estimate. The first is the error that arises from imperfect sensors. The second is the displacement error due to the measurement being taken at some distance, in space and time, from the analysis location. Our initial error models are based on the following simplifying assumptions:

1. Observations are unbiased.

2. Sensor errors from different observations are uncorrelated.

3. Errors in $u$ and $v$ components, measured or background, are uncorrelated.

4. Displacement errors and sensor errors are uncorrelated.

5. Displacement errors are independent of the component being measured.

With these assumptions, the error covariance matrix $C$ decomposes into the sum of a sensor error covariance matrix and a displacement error covariance matrix. The sensor error covariance matrix is diagonal, and the sensor error variances are known. The remaining task is the estimation of the displacement error covariance matrix.

The initial displacement error variance model is a linear function of the displacement between the observation location and the analysis location. The initial displacement error correlation model for two like components is a decreasing exponential function of the displacement between two observation locations. The displacement error covariance model for two non-orthogonal, non-parallel components must take into account the angle between the two components. We denote the angle between the observed component and the $u$ axis by $\theta$, with east at $0^\circ$, and north at $90^\circ$, and the displacement error in observation $i$ by $\delta_i^\circ$. Then the displacement error covariance for two observations is given by the following equation:

$$\text{Cov}(\delta_i^\circ, \delta_j^\circ) = \cos(\theta_1 - \theta_2)[\text{Var}(\delta_i^\circ)\text{Var}(\delta_j^\circ)]^{\frac{3}{2}}\text{Cor}(\delta_i^\circ, \delta_j^\circ)$$  \hspace{1cm} (2.4)

Unlike the multiple Doppler analysis, the OE solution is always numerically stable due to the inclusion of the background wind estimate. The inclusion of a $(u, v)$ data
point provides two component estimates at right angles, giving a maximum spread of azimuth angles. Since the error variances of the Doppler data are usually much smaller than the error variances of the other data, the OE solution closely matches the multiple Doppler solution at locations where the multiple Doppler problem is well conditioned. Otherwise, the analysis gives a solution that largely agrees with the radar observations in the component measured by the radars. The remaining component is derived from the vector estimates.

3. THE FORECASTING METHOD.

3.1. Thermodynamic Retrieval.

As discussed in the introduction a numerical simulation of the low-level wind field requires not only an accurate measure of the initial wind field, but also an estimate of the temperature field. Doppler radars generally give good observations of the radial velocity, with high spatial and temporal resolution, but no information about the temperature field. A technique has been developed over the last two decades to estimate the temperature field from observations of the wind field. This technique, called thermodynamic retrieval, was first developed by Gal-Chen (1978) and Hane and Scott (1978).

The Terminal Winds forecasting method uses essentially the retrieval method described by Gal-Chen. To describe this method, we first write the two horizontal momentum equations in a terrain-following coordinate system as,

\[
\rho u_t + FX = -(G^{1/2} p)_x - (G^{1/2} G^{13} p)_x \tag{3.1}
\]

\[
\rho v_t + FY = -(G^{1/2} p)_y - (G^{1/2} G^{23} p)_x \tag{3.2}
\]

where \((u, v)\) is the horizontal wind, \(p\) is the pressure, and \(FX\) and \(FY\) includes the effects of advection, Coriolis turning, sub-grid-scale mixing and surface drag. It also includes the horizontal filters that are used to damp 2\(\Delta x\) disturbances. \(G^{1/2}\) is the Jacobian of the transformation, and \(G^{1/2} G^{13}\) and \(G^{1/2} G^{23}\) are the two metric tensors. In the work that follows we assume that the terrain slope is small, so that the vertical gradient terms on
the right-hand side of (3.1) and (3.2) can be neglected. With this assumption, a horizontal Poisson equation for pressure is formed from (3.1) and (3.2):

\[ \nabla_H^2 (G^{\frac{1}{2}} p) = -FX_z - FY_y - \rho(u_z + v_y)t. \]  

(3.3)

The procedure for calculating the pressure and buoyancy can be summarized in the following manner:

1. Analyze the horizontal wind data to the model grid. In the work that follows we use a Cressman filter of the form;

\[ W = \frac{d^2 - d_r^2}{d_r^2} \]  

(3.4)

where \( d^2 = ((\delta x/\alpha)^2 + (\delta y/\alpha)^2 + \delta z^2) \) and \( (\delta x, \delta y, \delta z) \) is the distance from the model gridpoint to the data location, and \( d_r \) is the radius of influence.

Setting \( \alpha > 1 \) increases the weight given to data points located horizontally from the current model gridpoint and thus helps to preserve the vertical wind gradients that generally exist in the boundary layer.

2. Given the horizontal wind \((u, v)\) throughout the model domain, calculate the vertical velocity \( w \) from the continuity equation.

3. Use the model code to calculate \( FX \) and \( FY \) in (3.1) and (3.2).

4. Calculate the time tendency term \(-\rho(u_z + v_y)t\). Some care must be taken in calculating these terms, since any noise in the data will be exacerbated by the time-differencing procedure. In section 3.2 a method will be described for estimating the temporal terms.

5. Calculate the pressure deviation from (3.3) using Neumann boundary conditions. Add a constant to the pressure deviation at each level so that the value at the x-y location of the sounding is equal to zero. This can be done without loss of accuracy, since the retrieved pressure field is only accurate to within a horizontal constant (Gal-Chen 1978). This ensures that the pressure and temperature field in the model domain at the location of the sounding are equal to the sounding values.
Finally, calculate the buoyancy $B$ from the third equation of motion,

$$\rho w_t + FZ = -p_z - (G^{\frac{1}{2}} g/\gamma R_d)(p/T_0) + \rho g B, \tag{3.5}$$

where $FZ$ includes advection, Coriolis turning, sub grid-scale mixing, and the Rayleigh damping in the upper levels and $\gamma = c_p/c_v$.

### 3.2. Calculating Temporal Terms.

As mentioned above, care must be exercised in calculating the temporal terms to limit the amount of noise introduced in the retrieval scheme. Since only first order derivatives are required in (3.1) and (3.2), the obvious procedure is to fit a straight line to all of the data over a certain time interval. This is illustrated in Fig. 1, where the terminal winds data frequency of 5 minutes is used.

This method raises two questions which were addressed in Crook (1994):

1. At what time in the interval should the retrieval be performed? For operational purposes it is most expedient to perform the retrieval at the end of the assimilation window, since integration from that time onwards is into the future. However, as shown in Crook (1994) this produces the greatest error in the retrieved buoyancy field. The most accurate fields are produced when the retrieval is performed at the center of the assimilation window.

2. How long should the assimilation window be? To decrease the effect of noise in the data it is necessary to use a large assimilation window $\Delta t_a$. However as $\Delta t_a$ increases, the assumption of linearity becomes less valid. Furthermore, since the most accurate retrieval is achieved at the center of the assimilation window, using a longer window increases the time that one must integrate over before a prediction can be made. One possible method of ameliorating these problems is to fit a quadratic curve to the data instead of a linear curve. It is likely that this will give a better estimate of the tendency terms at the end of the assimilation window and hence improve the retrievals at the end of the window. In this report we examine the sensitivity of the predictions to the window length and the fit to the data.
RETRIEVAL PERFORMED EITHER AT CENTER OF WINDOW, OR AT END OF WINDOW.

ASSIMILATION WINDOW.

VELOCITY (u,v)

TIME (MINUTES)

Fig. 1 Schematic illustrating the different methods of fitting to the Terminal Winds velocity data. Both a linear and a quadratic least squares fit are shown. The initial fields and tendencies are taken from the least squares fit either at the center of the window, or the end.

3.3. Initializing the flow above the boundary layer.

The initialization technique described above is applied only in the planetary boundary layer (generally the lowest 1-2 km of the atmosphere). Above the boundary layer, the flow
is initialized with a single sounding and then adjusted so as to damp the vertical velocity with height (see Crook, 1994).

4. TESTS WITH MEMPHIS DEMVAL DATA.

In the summer of 1994, the FAA conducted a DemVal of ITWS at the Memphis airport. A map of the Terminal area around Memphis is shown in Fig. 2 with the location of the principal sensing systems indicated. We now describe the results from 2 days (June 9, 1994 and June 21, 1994) when significant gust fronts moved across the airport. The experiments that are described herein are listed in Table 2.

| Exp 1 | 1800 LT 6/9/94 | Centered, linear | 4 |
| Exp 2 | ... | End-time, linear | 4 |
| Exp 3 | ... | End-time, quadratic | 4 |
| Exp 4 | ... | End-time, quadratic | 5 |
| Exp 5 | 2245 LT 6/21/94 | Centered, linear | 4 |
| Exp 6 | ... | End-time, linear | 4 |
| Exp 7 | ... | End-time, quadratic | 4 |
| Exp 8 | ... | End-time, quadratic | 5 |
Fig. 2 The Terminal Winds domains for the 10 km and 2 km horizontal resolution grids. Each is centered on the Memphis airport. The name of the Doppler radars are centered on the radar locations. The diamonds show the locations of surface sensing systems. The center diamond represents the collection of surface stations at the airport which is comprised of an ASOS and 6 LLWAS stations. Also included in the figure are State boundaries.


a. Forecast Summary.

Around 1800 Local Time, a very strong gust front crossed the Memphis Airport. This system produced large hail and winds over 30 ms$^{-1}$ at the airport forcing the evacuation of the control tower. The storm passed over the airport, moving west to east, during a Northwest arrival push slightly after noon. The use of ITWS Storm Extrapolated Position allowed the controllers to keep the airport open approximately an extra 15 minutes reducing the number of aircraft that were required to divert to other destinations. The low-level wind field at 1800 Local Time is shown in Figure 3(a). The vectors shown have been
interpolated to the model grid from the Terminal Winds grid by using a Cressman filter with $d=4\text{km}$, $\alpha=4$. The wind vectors represent an average over the lowest 200 meters of the atmosphere, (the lowest grid box of the model). The size of the domain is 90 by 90 km.

Contoured in Fig 3(a) is the east-west component of the wind (contour interval of 2 $\text{ms}^{-1}$). A strong surge of westerly winds can be seen to the west of Memphis airport. The maximum wind is approximately $21 \text{ ms}^{-1}$ from $290^\circ$.

The retrieved buoyancy field is depicted in Fig. 4. This retrieval is performed at the center of a four timelevel window, using a linear least squares fit. The gust front is approximately $3^\circ\text{C}$ cooler than the air to the east.

The analysis 40 minutes later is shown in Fig 3(b). If the 10 $\text{ms}^{-1}$ isotach is used to define the leading edge of the gust front, then the front has moved approximately 42 km in 40 minutes (giving a speed of propagation of 17 $\text{ms}^{-1}$).

Shown in Fig. 3(c) is the 40 minute wind forecast from the initial conditions in 3(a). Again using the 10 $\text{ms}^{-1}$ isotach, the modeled wind surge has propagated 36 km in 40 minutes (giving a speed of propagation of 15 $\text{ms}^{-1}$). Note that the velocity gradient at the leading edge of the wind surge has sharpened significantly compared to the wind field at 1800 Local Time. This is fairly typical behavior for modeled gust fronts and is due to convergence at the leading edge of the front contracting the velocity and temperature gradients with time.
Fig. 3(a) Wind field at 1800 Local Time, June 9. Contoured is the east-west component of velocity with an interval of 2.0 ms$^{-1}$. The thick solid lines indicate the state boundaries of Tennessee, Mississippi and Arkansas.

Fig. 3(b) Verifying analysis at 1840 Local Time, June 9.
Fig. 3(c) 40 minute forecast verifying at 1840 Local Time, June 9.

Fig. 4 Retrieved perturbation temperature field at 1840 Local Time, June 9. Contour interval equals .25°C.
Although the numerical model has predicted the gust front speed reasonably well, there are significant differences between the forecast and observed wind fields. The most significant difference is in the northwest corner of the domain where strong northwesterlies were observed, while the model has forecast northeasterlies. As also found with the June 21 gust front, the model does reasonably well with the region of the gust front where the winds are well observed by the TDWR/NEXRAD pair and not so well where the winds are poorly observed. Hence the winds behind that section of the gust front which is heading directly towards the radar pair are well observed and forecast, while the winds to the north are not well observed and hence not forecast well. This is also shown in the retrieved buoyancy field in Fig. 4. Since the true gust front was, to a good approximation, a straight line feature propagating from west to east, it is reasonable to expect that the buoyancy was uniformly distributed behind the gust front. However, the retrieved buoyancy, which depends solely on the observed wind field, has a distinct maximum directly to the west of the radar pair, where the winds are well observed, and tapers off to the north and south. Since the gust front is a buoyancy driven feature, it is not surprising then that the best prediction of the gust front is in the center of the domain.

b. Verification.

To verify the model’s performance we have calculated the mean vector wind difference (MVD) between the forecast 3(c) and analysis 3(b). (Note that we have used the word difference and not error since we are comparing against an analysis.) The MVD is given by:

\[
MVD = \frac{1}{N} \sum_{i=1}^{N} \left[ (u_i^f - u_i^o)^2 + (v_i^f - v_i^o)^2 \right]^{\frac{1}{2}}
\]  

(4.1)

where \( N \) is the number of gridpoints used for the verification, \((u_i^f, v_i^f)\) is the forecast wind at point \( i \), and \((u_i^o, v_i^o)\) is the analyzed wind. Since we are primarily interested in forecasts of the low level winds, we only perform the verification over the lowest model level (200 meters). Also, since we are not updating the lateral boundary conditions with time, the verification is restricted to an inner domain of 70 by 70 km.

The MVD for experiment 1 at 20 and 40 minutes, is plotted in Fig. 5. For comparison,
we also plot the MVD of persistence (which is the forecast that the wind field does not change with time). After 40 minutes the MVD of persistence is 11.4 ms$^{-1}$. This represents a significant wind change and indicates the strength of this gust front. Previous gust front events examined in Colorado have had persistence MVDs of around 3-5 ms$^{-1}$ in 40 minutes, (see Crook and Tuttle, 1994).

The MVD of the forecast is 7.8 ms$^{-1}$ after 40 minutes, which represents a 32% improvement over persistence.

![Graph](image)

**Fig. 5** Mean Vector-wind Difference (MVD) for Exp 1 compared with persistence. Simulation commences at 1800 LT, June 9, 1994.

c. **Sensitivity to Data Fitting.**

The forecast shown in Fig. 3 was performed using a centered, linear least squares fit to 4 time levels. This means that to perform a forecast beginning at 1800 Local Time,
required data at 1810. In an operational environment, this would reduce the utility of such a forecast. We now examine other methods of data fitting that would be more useful in an operational environment. The first method is again a linear least squares fit, however, the velocity fields at the end of the time window are used for initialization, (Experiment 2). So that comparison can be made with the results from Experiment 1, the forecast begins at 1800, (hence it uses data at 1745, 1750, 1755 and 1800). We argue that if the forecast in Experiment 2 is as good as in Experiment 1, then the second method is more useful since it doesn’t require data at 1810.

The MVD for Experiment 2 at t=20 and 40 minutes are listed in Table 3. At 40 minutes, the errors are very similar between experiments 1 and 2. However, experiment 2 has a larger error at 20 minutes. This is most likely due to the fact that using velocity fields at the end of the assimilation window, places the retrieved cold air a short distance behind the wind surge (see Crook (1994), Fig. 5(c)). It then takes some time (5-10 minutes) for the cold air to catch up to the wind surge before the surge begins to propagate forward.

A possible method of reducing this problem is to fit a quadratic curve to the data. As long as the data are not too noisy, then this should produce a better estimate of the wind tendency at the end of the assimilation window. In Experiment 3, we fit a quadratic to the data in the same time window (1745, 1750, 1755 and 1800) and commence the forecast at 1800. The MVD in Experiment 3 is listed in Table 3. As can be seen, it produced a better forecast than both Experiments 1 and 2 at 40 minutes, a better forecast than Experiment 2 at 20 minutes, although slightly degraded compared to Experiment 1 at 20 minutes.

Fitting a quadratic to 4 data levels, overdetermines the solution only by an order of 1 (3 variables fit to 4 data levels). If the data are particularly noisy, then this may not produce sufficient smoothing. In Experiment 4, 5 levels of data are used (1740, 1745, 1750, 1755 and 1800). The results from Experiment 4 (Table 3) indicate that at both 20 and 40 minutes the forecast is slightly better than the forecast produced from a quadratic fit over 4 time levels (experiment 3).
TABLE 3. Verification of June 9 forecasts.

<table>
<thead>
<tr>
<th></th>
<th>MVD at 20 min. (m/s)</th>
<th>Persistence (m/s)</th>
<th>MVD at 40 min.</th>
<th>Persistence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp 1</td>
<td>3.7</td>
<td>5.9</td>
<td>7.8</td>
<td>11.0</td>
</tr>
<tr>
<td>Exp 2</td>
<td>4.9</td>
<td>...</td>
<td>7.8</td>
<td>...</td>
</tr>
<tr>
<td>Exp 3</td>
<td>5.9</td>
<td>...</td>
<td>7.7</td>
<td>...</td>
</tr>
<tr>
<td>Exp 4</td>
<td>5.4</td>
<td>...</td>
<td>7.5</td>
<td>...</td>
</tr>
</tbody>
</table>


a. Forecast Summary.

The second gust front case that we have examined occurred late in the day on June 21. A distinct gust front propagated through the Memphis area at around 2300 Local Time. Unlike the June 9 case, this gust front was not accompanied by significant convection. The wind field at 2245 Local Time is shown in Fig. 6(a). Northwesterly winds can be seen just to the west of Memphis Airport. The winds behind the gust front reach approximately $10 \text{ ms}^{-1}$, which is considerably less than the $21 \text{ ms}^{-1}$ observed in the June 9 case. The gust front propagated at approximately $6 \text{ ms}^{-1}$ from a direction of $300^\circ$.

The buoyancy field, at 2245 Local Time, is shown in Fig. 7. The minimum temperature difference behind this gust front is $1.9^\circ\text{C}$. Again we notice that the minimum temperature occurs in the region where the winds are directed towards the radar pair, and falls off both north and south of that region.

The observed velocity field 40 minutes later is shown in Fig. 6(b). The northwesterly winds have now propagated over Memphis Airport. There is also a distinct wind maximum 20 km to the north of the Airport.

The forecasted wind field is shown in Fig. 6(c). This forecast was performed by using a centered linear least squares fit to four time levels. As can be seen the model has propagated the northwesterly wind surge over Memphis Airport. However, the wind maximum just to the north of the airport has not developed in the simulation.
Fig. 6(a) Wind field at 2245 Local Time, June 21. Contoured is the east-west component of velocity with an interval of 1.0 m/s⁻¹.

Fig. 6(b) Verifying analysis at 2325 Local Time, June 21.
Fig. 6(c) 40 minute forecast verifying at 2325 Local Time, June 21.

Fig. 7 Retrieved perturbation temperature field at 2245 Local Time, June 21. Contour interval equals 0.25°C.
b. Verification.

The skill scores for Experiment 5 are plotted in Fig. 8. The MVD for the model forecast at 40 minutes is 3.2 ms\(^{-1}\). This represents only a 12\% improvement over persistence at that time (MVD = 3.6 ms\(^{-1}\)). Also at 20 minutes, the model forecast is slightly worse than persistence.

![Graph of Mean Vector-wind Difference (MVD) for Exp 5 compared with persistence.](image)

Fig. 8 Mean Vector-wind Difference (MVD) for Exp 5 compared with persistence. Simulation commences at 2245 LT, June 21, 1994.

The skill scores for experiment 6 (end-time linear least squares fit to 4 time levels), experiment 7 (end-time quadratic least squares fit to 4 time levels) and experiment 8 (end-time quadratic least squares fit to 5 time levels) are listed in Table 4. As can be seen, all of the end-time simulations improve over the centered-time simulation. The best result came from Experiment 6, with a MVD of 2.7 ms\(^{-1}\) at 40 minutes which represents a 30\%
improvement over persistence.

TABLE 4. Verification of June 21 forecasts.

<table>
<thead>
<tr>
<th></th>
<th>MVD at 20 min. (m/s)</th>
<th>Persistence (m/s)</th>
<th>MVD at 40 min.</th>
<th>Persistence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp 5</td>
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<td>1.8</td>
<td>3.2</td>
<td>3.6</td>
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<tr>
<td>Exp 6</td>
<td>1.5</td>
<td>...</td>
<td>2.7</td>
<td>...</td>
</tr>
<tr>
<td>Exp 7</td>
<td>1.9</td>
<td>...</td>
<td>3.1</td>
<td>...</td>
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<tr>
<td>Exp 8</td>
<td>1.6</td>
<td>...</td>
<td>2.8</td>
<td>...</td>
</tr>
</tbody>
</table>

5. DISCUSSION OF RESULTS.

Results from the June 9 and 21 gust front cases indicate that the numerical model has some skill at predicting low-level wind surges observed by the Terminal Winds system. It should be emphasized that we have only examined two cases herein, and hence the level of skill is difficult to ascertain. To quantify the level of skill and the sensitivity to different model parameters would require a much larger statistical sample (> 20 events). Such a study is beyond the scope of this report. Consequently, we can only make some preliminary statements from this work.

(1) The numerical model appears to be most successful at predicting the portion of the gust front where the winds are directed towards the radar pair. It was less successful at predicting the section of the gust front where the winds are nearly tangential to the radar pair. This behavior manifests itself in the retrieved buoyancy field. In both cases, the retrieved buoyancy was greatest behind that section of the gust front which was propagating towards the radar pair. The retrieved buoyancy then dropped off, both north and south of that region.

(2) There was no indication that calculating initial fields and retrieved buoyancies at the end of the assimilation window, is deleterious to the wind forecasts. Calculating the initial fields at the end of the assimilation period is important for operational purposes, since it allows a forecast to be made as soon as the data are available.

(3) In the study of Crook (1994) with simulated data, it was found that performing an end-time linear least squares fit resulted in a mismatch between the velocity fields and
their tendencies, which placed the cold air some distance behind the gust front. In order to alleviate this problem, tests were performed with a quadratic fit to the data over 4 or 5 time levels. The results were inconclusive as to whether this produced a better forecast than the linear fit.

6. CONCLUSIONS AND RECOMMENDATIONS.

We have been reasonably encouraged with the performance of the model with the Terminal Winds dataset. It should be emphasized that (1) the Terminal Winds analysis procedure is continually being refined and (2) that short term numerical wind forecasting is in its early stages. It is reasonable to expect that both the dataset and the forecasting methods will improve with time which should result in improvements in model skill.

Based on the results from this study and from previous work on short-term wind forecasting we recommend;

(1) That a reflectivity tracking method be incorporated into the Terminal Winds analysis system. Previous studies (Tuttle and Foote (1990)) have shown that the low level winds can be retrieved by tracking small-scale reflectivity features in the boundary layer. This should produce a better estimate in regions where the low-level wind is more tangential to the radar pair. This additional data source should be relatively simple to incorporate into the Terminal Winds analysis procedure.

(2) The inclusion of as much surface wind and temperature data as possible. The results from Crook and Tuttle (1994) indicated that surface data can improve low-level wind forecasts significantly. Surface data assists the forecasts by (1) giving a more reliable estimate of the low-level wind in regions which are poorly sensed by Doppler radars and (2) giving a temperature observation which can be incorporated with the retrieved temperature field.

(3) That a large dataset (> 20) of gust front cases be collected in order to test the model's skill and its sensitivity to various parameters.
REFERENCES.


