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Development of a Weather Running Estimate-Nowcast Capability for the U.S. Army IMETS

by Teizi Henmi, Robert Dumais, and Richard Okrasinski

ARL-TR-3647 **September 2005**

NOTICES

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REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)* September 2005	**2. REPORT TYPE** Final	**3. DATES COVERED (From - To)**

4. TITLE AND SUBTITLE Development of a Weather Running Estimate-Nowcast Capability for the U.S. Army IMETS	**5a. CONTRACT NUMBER**
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Teizi Henmi, Robert Dumais, and Richard Okrasinski	**5d. PROJECT NUMBER**
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army Research Laboratory Computational and Information Sciences Directorate Battlefield Environment Division (ATTN: AMSRD-ARL-CI-EM) White Sands Missile Range, NM 88002-5501	**8. PERFORMING ORGANIZATION REPORT NUMBER** ARL-TR-3647
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army Research Laboratory 2800 Powder Mill Road Adelphi, MD 20783-1145	**10. SPONSOR/MONITOR'S ACRONYM(S)**
	11. SPONSOR/MONITOR'S REPORT NUMBER(S) ARL-TR-3647

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

A nowcast/short-range forecast method, over the domains of approximately 100 km by 100 km with grid resolution of 1.5 to 2.0 km, has been developed for the Integrated Meteorological System (IMETS). Meteorological data available in the IMETS, including Mesoscale Model Version 5 (MM5) forecast, surface, and upper-air sounding data, are used for the computation. Three-dimensional distributions of temperature, dew-point temperature, and horizontal wind vector components can be forecasted. The method is evaluated over two different areas: Dallas (TX) and Denver (CO). It was shown that the present method was valid up to 3 h over the Dallas domain, and up to 2 h over the Denver domain. Although further studies are needed over different areas and seasons, it is tentatively concluded that the present forecasting method can be used at least for 2 h.

15. SUBJECT TERMS

Nowcast, objective analysis

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Teizi Henmi
a. REPORT U	**b. ABSTRACT** U	**c. THIS PAGE** U	SAR	40	**19b. TELEPHONE NUMBER** (*Include area code*) 505-678-3519

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

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Executive Summary

A computationally fast, mesoscale meteorological analysis and very short range prediction (nowcasting) capability has been developed for the U.S. Army, specifically for the Integrated Meteorological System (IMETS), which is the Army's tactical weather system. This tactical analysis and nowcast capability is currently referred to as the Weather Running Estimate-Nowcast (WRE-N) by the U.S. Army Research Laboratory, White Sands Missile Range, NM, which is serving as the Army lead in its development. The WRE-N discussed in this report is an initial implementation of such a capability, configured for a domain of approximately 100 km by 100 km, with a horizontal grid resolution of 1.5 km. Additionally, this WRE-N has been tailored to accept meteorological data sources routinely available to the IMETS, including Air Force Weather Agency (AFWA) Mesoscale Model Version 5 (MM5) numerical forecasts, surface sensor observations, and upper-air radiosonde observations. Finally, this implementation allows three-dimensional gridded distributions of temperature, dew-point temperature, and horizontal wind vector components to be analyzed and nowcasted.

The method is evaluated over two different geographic areas: one centered near Dallas, TX, and the other near Denver, CO. This report shows that the method appeared to add value (when compared to AFWA 15-km MM5 background forecasts) for up to 3 hr over the Dallas domain (fairly uniform terrain) and up to 2 hr over the Denver domain (complex terrain). Although further studies are needed over different areas and seasons, we tentatively conclude that the present WRE-N method, which is based on extrapolation, can be used for at least two hours for many meteorological scenarios, especially when the background forecast model (the operational AFWA MM5) is of good quality on the mesoscale.

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1. Introduction

For U.S. Army operations, being able to accurately update high spatial and temporal resolution meteorological information, generated by fusing or assimilating current local meteorological observational data, is more desirable than relying on results obtained by previously executed model forecasts alone. Although current state-of-the-art numerical weather prediction (NWP) models offer an unprecedented capability to simulate small-scale mean atmospheric structures, individual deterministic model solutions tend to suffer from day-to-day spatial and temporal errors in amplitude, phase, and variability. These errors are due to many reasons, whose discussion is beyond the scope of this report.

To correct for these kinds of errors and model biases, it is necessary to assimilate real meteorological observational data through, for example, NWP model forecast cycling. The advanced assimilation methods that have been developed over the past few decades now offer dynamically, physically consistent and statistically optimal methods of "correcting" NWP model tendencies on the fly. If the "current" weather situation is accurately analyzed, it may be possible to reasonably predict very short-term weather situations (nowcasting). Our ability to accomplish this will increase as techniques continue to improve and better methods of assimilating observed cloud-scale fields and dynamically coupling them to NWP model fields are produced.

Rapid adjustments of intelligence and warfighter decision making tools, to account for changes in the local battlefield's three-dimensional (3D) environmental state (which often deviate from the existing operational NWP model forecast guidance), are known as Weather Running Estimates (WREs). For the Army, near-surface meteorological changes on timescales ranging from minutes to a few hours are critical to ground operations. Such changes are classified as meso-γ (1- to 10-km grid spacing) scale phenomena (Orlanski, 1975). This range is also commonly referred to as the "cloud" or "storm" scale.

Nowcasting is a method of diagnosing the current weather situation by combining existing forecast guidance with observational data, using various methods of analysis/fusion and assimilation, and then extending this meteorological "picture" forward in time to produce a very short-range forecast or prediction (Browning, 1982). The predictive component can be produced in many ways, such as through cycling (coupling analyses to prognostic NWP models), extrapolation, statistical methods, or expert system approaches. The Weather Running Estimate-Nowcast (WRE-N) incorporates a 3D gridded analysis (the WRE) and a 3D short-range gridded prediction counterpart (the Nowcast).

Using conventional observational data along with operational Mesoscale Model Version 5 (MM5) NWP model data produced at the U.S. Air Force Weather Agency (AFWA), a relatively simple and fast (in terms of execution) WRE-N system has been developed, building upon earlier analysis techniques constructed at the U.S. Army Research Laboratory (ARL), White Sands Missile Range, NM (Henmi, 2003). In the current WRE-N system, separate surface and upper-air meteorological analyses are first produced univariately. To produce a surface analysis, local surface observations and concurrent

NWP model forecast data are composed using a successive correction method (Sashegyi and Madala, 1994). Similarly, the upper-air analyses (produced for many predetermined levels above ground) are a composition of upper-air radiosonde soundings and NWP model forecast data, using the same scheme. After both the surface and upper-air analyses have executed, similarity theory formulae named MARIAH (Rachele et al., 1995) are used to couple the surface and upper-air analyses into a single set of 3D fields. This 3D "snapshot" is the WRE component of the WRE-N system. The analysis method used to produce the WRE has been previously statistically evaluated (Henmi and Dumais, 2004) over Utah using the University of Utah's MesoWest data (Horel et al., 2002). That study showed that this method produced much better statistical results for temperature, dew-point temperature, and wind vectors as compared to previously generated background forecast fields from the Pennsylvania State University/National Center for Atmospheric Research MM5.

The U.S. Army's Integrated Meteorological System (IMETS) regularly receives (from AFWA) surface observation data (such as METAR), World Meteorological Organization (WMO) upper-air radiosonde sounding data, and WMO gridded binary (GRIB) data produced from operational forecasts of the MM5. The MM5 forecast data are typically produced twice daily at a horizontal grid spacing of 15 km. Using the AFWA operational MM5 fields for both current and "future" background field data, the WRE-N method has been developed and adapted for the IMETS.

To produce the Nowcast component of the WRE-N, the successive corrections analysis method has been extended to make a short-range "prediction" for the period out to 3 h forward. The WRE-N has been nominally configured for a domain of approximately 100 km by 100 km and for a horizontal grid spacing of about 1.5 km. For clarification, the successive corrections approach is used to produce the WRE "current" analysis, while a linear-interpolation method is used to extrapolate the WRE fields forward to produce the short-range nowcast. In extrapolating the WRE analysis forward, the AFWA MM5 fields (valid at the desired forward times) are used as background data. The method has recently been applied to two different geographical domains and evaluated statistically, with the preliminary results presented later in this report.

2. Data Used

The WRE-N is designed to incorporate the data most readily available in the current IMETS system, which includes digital terrain elevation data and both observational and NWP model forecast data supplied from AFWA (surface, upper-air radiosonde, and GRIB-formatted MM5 output).

2.1 Elevation Data

The elevation data file, which encompasses the WRE-N area of interest (AOI), is produced by reading the Digital Terrain Elevation Data (DTED) Level 0 from the Defense Mapping Agency (DMA). An existing IMETS computer program produces a terrain elevation data file for a 161-by-161 gridded domain centered at the desired WRE-N AOI, with the data interpolated from the native 30 arc second resolution to the desired WRE-N 1.5-km grid spacing. This is done on a pseudo-Universal Transversal Mercator (UTM) grid, which is the same grid used by the WRE-N. Since the generated elevation data covers a domain somewhat larger than that required for the WRE-N (100 km by 100 km), the actual terrain data used by WRE-N is clipped from the original file of 161-by-161 grid points.

2.2 MM5 Data

From the GRIB-formatted MM5 forecast data files sent from the AFWA, vertical distributions, or “model soundings,” of forecast fields at 3-h output intervals are extracted for the AOI region and placed into ASCII input files. These files include MM5 data that are interpolated to both the desired WRE-N “current” hour and 3 hr forward from that time. The base time of the MM5 must be between 9 and 24 hr earlier than the WRE 0 hour. A portion of the data contained within the WRE-N input MM5 ASCII files is shown in figure 1.

```
22Apr 12Z
15.00
121
43
     32.326
    -97.798
262.00
   74.35 18209.64  202.70   15.81   4.70    -6.50
   91.68 16967.91  201.90   15.45   21.10   -8.90
  110.44 15868.92  201.90   10.87   30.50   -6.10
  130.88 14853.94  206.30   11.21   33.80  -12.10
  152.37 13925.03  211.40   11.55   38.10  -21.50


  536.17  5244.52  263.10   22.35   14.50     .90
  565.84  4827.54  265.90   21.80   13.10    -.70
  595.47  4428.24  268.60   20.40   12.40   -3.30
  625.05  4045.06  271.30   19.30   12.40   -5.90

  963.80   431.50  294.10    5.91    -.30   -4.60
  971.50   362.55  294.10    5.14     .00   -4.30
  976.94   314.16  294.20    4.58     .30   -3.70
  980.57   282.03  294.30    4.18     .40   -2.90
  981.72   272.00  294.38    4.18     .35   -2.55
  982.64   264.00  294.38     4.18    .21   -1.54
```

Figure 1. A portion of an ASCII MM5 data file used as WRE-N input, extracted from the MM5 GRIB datasets transmitted from AFWA.

The top lines of each data file contain the valid date and forecast time of the MM5 forecast data, the MM5 model grid resolution, the number of MM5 grid point "soundings" in the file, and the number of MM5 vertical layers. Subsequent lines include the latitude, longitude, and model terrain elevation for each MM5 grid point sounding, followed by the forecast data for the meteorological fields at each model sigma level. The data columns contain pressures (mb), heights above sea level (m), temperatures (°K), dew-point depressions (°C), and wind vector components, *u* and *v* (m/s).

2.3 Surface Data

Surface meteorological observations are input into the WRE-N as ASCII formatted files and contain pressure (mb), temperature (°C), dew-point temperature (°C), wind speed (m/s), and wind direction (deg) data. Figure 2 shows a portion of the WRE-N input surface meteorological data file.

```
Pressure (mb)
7
  32.680000 -96.860001 22Apr 11:53  1011.90
  32.810001 -97.360001 22Apr 11:53  1012.10

  33.180000 -96.580002 22Apr 11:53  1013.50
  33.200001 -97.180000 22Apr 11:53  1013.10
Temperature (C)
12
  32.560001 -97.300003 22Apr 12:05   17.00
  32.660000 -97.099998 22Apr 12:09   17.00

  33.200001 -97.180000 22Apr 11:53   15.00
  33.650002 -97.199997 22Apr 12:05   12.00
Dewpoint Temperature (C)
12
  32.560001 -97.300003 22Apr 12:05   16.00
  32.660000 -97.099998 22Apr 12:09   16.00

  33.200001 -97.180000 22Apr 11:53   11.00
  33.650002 -97.199997 22Apr 12:05    9.00
Wind Speed (m/s)
12
  32.560001 -97.300003 22Apr 12:05    1.54
  32.660000 -97.099998 22Apr 12:09    1.54

  33.200001 -97.180000 22Apr 11:53    3.60
  33.650002 -97.199997 22Apr 12:05    2.06
Wind Direction (deg)
12
  32.560001 -97.300003 22Apr 12:05   250.00
  32.660000 -97.099998 22Apr 12:09   240.00

  33.200001 -97.180000 22Apr 11:53      .00
  33.650002 -97.199997 22Apr 12:05   340.00
```

Figure 2. A portion of an ASCII surface meteorological data file used as WRE-N input, containing pressure, temperature, dew-point temperature, wind speed, and wind direction for different observation locations.

2.4 Upper-Air Radiosonde Data

The upper-air radiosonde observation data are ingested into the WRE-N as ASCII formatted files, similar to the MM5 and surface observations. An abbreviated portion of a WRE-N input upper-air radiosonde data file is shown in figure 3. Information about latitude; longitude; height above ground; date and hour of observation; and number of levels are given in the first three lines. Pressure (mb), height above sea level (m), temperature (°C), dew-point temperature (°C), wind speed (kn), and wind direction (deg) data are also given. All missing data are expressed as “-999.0.”

```
32.830002 -97.300003 196.000000
20Apr 00:00
83
  1000.00   97.00 -999.00 -999.00  -999.00  -999.00
  988.00   196.00   24.40   17.40    6.00   160.00
  925.00   773.00   18.40   15.70   13.00   170.00
  885.00  -999.00   14.80   14.50  -999.00  -999.00
  850.00  1493.00   13.40   11.80   13.00   195.00
  800.00  -999.00   10.00    9.20  -999.00  -999.00
  792.00  -999.00   10.60    8.80  -999.00  -999.00
  784.00  -999.00   13.60    8.70  -999.00  -999.00

   60.00  -999.00   -64.70   -81.70  -999.00  -999.00
   50.00  20620.00   -62.90   -80.90    5.00   270.00
   43.00  -999.00   -59.70   -79.70  -999.00  -999.00
   34.00  -999.00   -60.10   -79.10  -999.00  -999.00
   30.00  23810.00   -56.10   -76.10    3.00   285.00
   27.00  -999.00   -52.70   -74.70  -999.00  -999.00
   23.00  -999.00   -54.10   -75.10  -999.00  -999.00
   20.00  26410.00   -50.70   -73.70    7.00   240.00
   17.00  -999.00   -46.10   -70.10  -999.00  -999.00
   12.00  -999.00   -43.70   -66.70  -999.00  -999.00
   10.00  31050.00   -40.50   -66.50   18.00   250.00
   9.00  -999.00   -38.50   -64.50  -999.00  -999.00
```

Figure 3. A portion of an ASCII upper-air radiosonde sounding data file used as WRE-N input, containing pressure, height above sea level, temperature, dew-point temperature, wind speed, and wind direction.

Figure 4 shows an example of one of the WRE-N domains evaluated in this report, depicting the terrain and meteorological data sources used as inputs. The elevation contours shown are for a 75-by-75 grid point domain with a 1.5-km horizontal resolution, centered at 32.83° N. and 97.30° W. The locations of the MM5 grid points (15-km resolution) are marked with an asterisk (*), and surface and upper-air data locations are represented with an “S” and a “U,” respectively. The city of Dallas, TX, is located near the center area of this domain, referred to as the Dallas domain in this report.

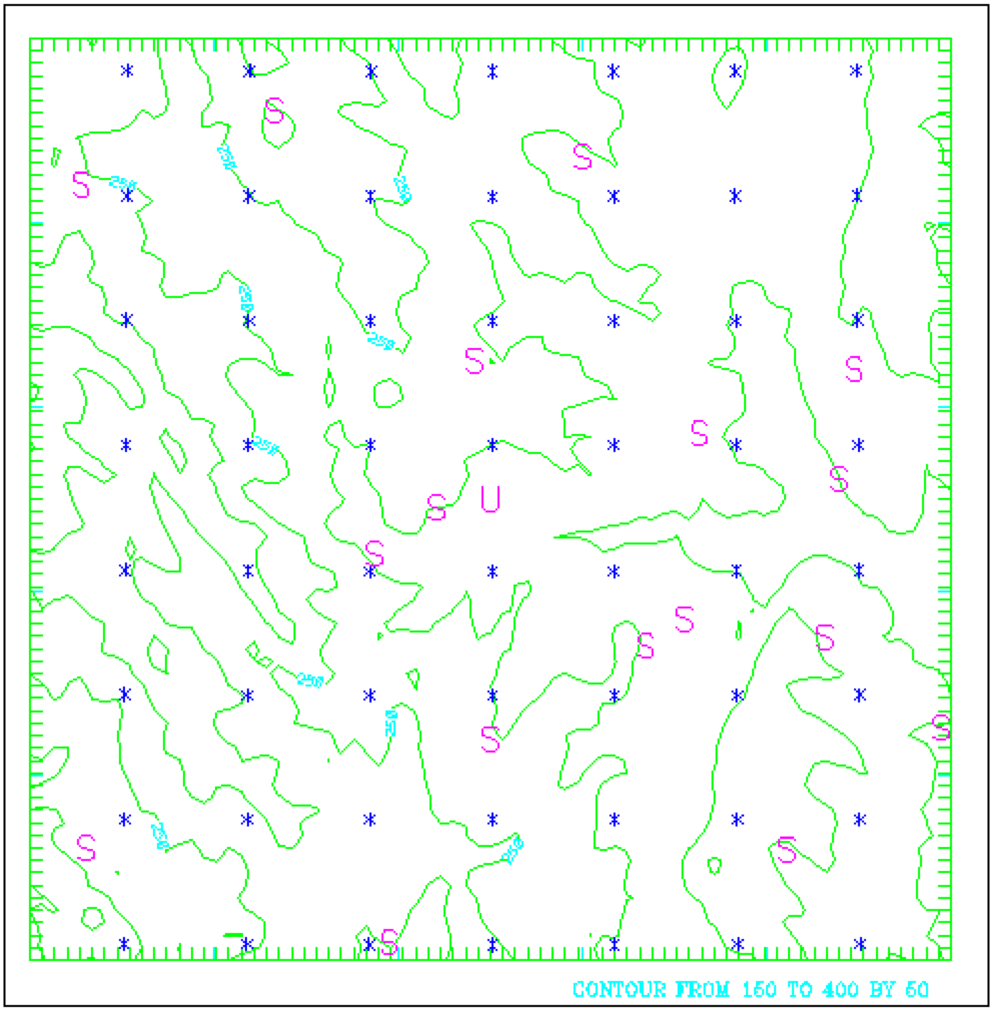

Figure 4. Elevation contour distribution for the domain of 75-by-75 grid points with 1.5-km grid spacing, centered at 32.83° N. and 97.30° W. (Dallas domain).

NOTE: The “*” symbol represents MM5 grid points, while “S” and “U” represent locations of surface and upper-air radiosonde meteorological observations, respectively.

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3. Analysis Methods to Produce WRE

3.1 3D Analysis of MM5 and Upper-Air Radiosonde Data

The 15-km resolution MM5 forecast data, as shown in figure 1, are first interpolated spatially 1) onto predetermined height levels above mean sea level and 2) to the WRE-N grid point locations at the finer horizontal grid resolution (1.5 km).

There are differences between the terrain heights of grid points interpolated from MM5 forecast data and those obtained from DTED Level 0. Three-dimensional temperature and pressure field errors, due to the terrain height difference, are corrected as follows:

Surface temperature and pressure are recalculated as

$$T_s = T_{s0} + (\frac{dT}{dz}) * \Delta Z \tag{1}$$

$$P_s = P_{s0} + (\frac{dP}{dz}) * \Delta Z \tag{2}$$

where

T_s: corrected surface temperature,

P_s: corrected surface pressure,

T_{s0}: surface temperature interpolated from MM5 data,

P_{s0}: surface pressure interpolated from MM5 data,

dT/dz: temperature gradient (6.5 °C per 1,000 m),

dP/dz: pressure gradient (9.0 mb per 100 m),

ΔZ: terrain height difference, $Z_{s0} - Z_s$,

Z_{s0}: terrain height interpolated from MM5 data, and

Z_s: terrain height from DTED Level 0.

Vertical temperature profile is recalculated as

$$T(Z) = T_s + (\frac{T(Z_c) - T_s}{Z_c - Z_s}) * (Z - Z_s) . \tag{3}$$

Here Z_c is the height determined empirically to correct vertical temperature profile.

Vertical pressure profile is recalculated using the hydrostatic equation:

$$P(Z_2) = P(Z_1) * \exp\left\{ -(\frac{g}{2R})(Z_2 - Z_1)(\frac{1}{T(Z_1)} + \frac{1}{T(Z_2)}) \right\} . \tag{4}$$

After these steps are accomplished, the data are then vertically interpolated once again to the vertical coordinate levels of the WRE-N. This sigma-*z* vertical coordinate of the WRE-N is defined as

$$z^* = \overline{H} \frac{z - z_g}{H - z_g} \tag{5}$$

where

z = the Cartesian vertical coordinate,

z_g = the ground elevation,

$\overline{H}$ = the material surface top of the model in the z^* coordinate, and

H = the corresponding height in the z coordinate defined by $H = \overline{H} + z_{g\max}$, where

$z_{g\max}$ = the maximum value of the terrain elevation in the domain of the WRE-N.

Currently, the vertical extent of the model ($\overline{H}$) is 7,000 m above the highest grid point elevation of the domain.

The following procedures are taken to interpolate the 15-km resolution MM5 forecast data to the 3D spatial locations of the WRE-N AOI:

1. MM5 parameters (temperature, dew-point temperature, and horizontal u and v wind components) are vertically interpolated to 30 predetermined vertical levels (z_i, $i = 1, 30$).
2. Horizontal interpolation of MM5 parameters (on z_i levels) to WRE-N grid point locations are performed for each parameter, using a $1/r^2$ weighting factor, where "r" is the distance between the MM5 grid point and the WRE-N grid point.
3. An arbitrary parameter φ on a z_i level is linearly interpolated to a z^* level of the WRE-N grid:

   $$\varphi(z^*) = \varphi_k + \frac{(\varphi_{k+1} - \varphi_k)}{(\zeta_{k+1} - \zeta_k)}(z_{st} - \zeta_k) \tag{6}$$

   where z_{st} is the Cartesian height above sea level of the z^* level, calculated from equation 1 as

   $$z_{st} = z_g + z^* \frac{(\overline{H} + z_{g\max} - z_g)}{\overline{H}} \tag{7}$$

   and ζ_k is the height of the k^{th} z_i level.

If there are no upper-air radiosonde sounding data available for a desired time, the 3D data of $\varphi(z^*)$ (as determined by equation 6) are used as the 3D background dataset for the creation of the WRE-N. For the nowcast periods of the WRE-N (t_0+30, t_0+60, t_0+90, t_0+120, t_0+150, t_0+180 min), this is how background MM5 fields are always generated, since no radiosonde data are available at these times. If there are local upper-air radiosonde sounding data available at the WRE/analysis time (t_0), the 3D MM5 data calculated in equation 2 are also composed with observed upper-air radiosonde sounding data as follows:

1. At each radiosonde location, sounding data (such as horizontal wind vector components, temperature, and mixing ratio) are vertically interpolated to the z_i levels using a linear interpolation method.
2. At each z_i level, the successive correction method is performed using the MM5 3D data generated in equation 6 as first-guess background data.
3. Linear vertical interpolation from z_i to z_{st} is performed for each WRE-N parameter and grid point.

3.2 Surface Data Analysis

Upon completion of the upper-air analyses described in section 3.1, a separate set of surface analyses are performed for each WRE-N parameter. Using the AFWA operational 15-km resolution MM5 as background data, objective analyses of surface temperature, dew-point temperature, and horizontal *u* and *v* wind vector components are made. The following variant of the successive correction method is used in these analyses.

For a given analysis time, if $\varphi_a(i, j)$ is the analyzed value of some meteorological parameter at grid point (i, j) and $\varphi_b(i, j)$ is the corresponding MM5 background value for that parameter (at that grid point), we can write

$$\varphi_a(i,j) = \varphi_b(i,j) + \sum_{k=1}^{m} w_{k,ij}(\varphi_{o,k} - \varphi_{b,k}) \tag{8}$$

where $\varphi_{o,k}$ is the observation at the k^{th} location, $w_{k,ij}$ is the weight for each observation, $\varphi_{b,k}$ is the value of the background at the observation point derived by a bilinear interpolation method, and *m* is the number of observations.

The weighting factor is defined as

$$w_{k,ij} = \frac{1}{r_{k,ij}^2} \tag{9}$$

where $r_{k,ij}$ is the distance between the k^{th} observation point and the grid point (i, j).

The method is repeated in an iterative fashion, so that the background field is updated by the latest analysis after each iteration:

$$\varphi_a(n+1) = \varphi_a(n) + \sum_{k=1}^{m} w_{k,ij}(\varphi_{o,k} - \varphi_{a,k}(n)) \tag{10}$$

where $\varphi_a(n)$ is the value of the analysis at the grid point after the n^{th} iteration, and $\varphi_{a,k}(n)$ is its value interpolated for the k^{th} location after the n^{th} iteration.

In this development, the iteration was repeated three times, for practical purposes, to obtain the final value.

3.3 MARIAH Similarity Formulae

The equations and approach for determining the similarity scaling constants for wind, temperature, and specific humidity—referred to as MARIAH (Rachele et al., 1995)—are used to combine surface and upper-air analysis data. For practical purposes, it is assumed that the lowest level above ground of the upper-air analysis data is modified by the surface analysis. Details of this method have been reviewed by Henmi and Dumais (2004).

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4. Nowcast Method to Complete WRE-N

After the analysis (WRE) component of the WRE-N (described in section 3), the following procedures are used to produce a nowcast out to 3 h for the same domain, the final component of the WRE-N system.

For the current WRE time (time = t_0), an arbitrary parameter, such as temperature, dew-point temperature, or u and v wind vector components, is expressed by $X_{0,}$ where X represents the meteorological parameter. For the t_0 + 3 h nowcast time (time = t_3), only the 3D MM5 forecast data is available (no observations exist in the future). These MM5 forecast data are then analyzed at time t_3 for the domain of interest, using the methods discussed in section 3. An arbitrary MM5 forecast parameter at time t_3 is expressed by X_3.

The time rate of change of parameter X between time t_0 and t_3 is calculated as

$$\frac{dX}{dt} = \frac{X_3 - X_0}{t_3 - t_0}. \tag{11}$$

If no previous nowcast has been made within the 3-h period preceding time $t_{0,}$ a nowcast for the parameter X at time t between t_0 and t_3 is generated by

$$X_t = X_0 + \beta \bullet \frac{dX}{dt} \bullet (t - t_0). \tag{12}$$

Here, β is an empirical parameter to be determined in section 6.

If a previously generated WRE-N dataset that has been generated within Δt prior to the currently desired WRE-N time (t_0) exists, the most recently generated WRE-N fields will be utilized in producing the new nowcast. To do so, new variables $X_{\Delta t}$ are defined for X at Δt. The time rate of change of X from Δt to t_3 is calculated as

$$\left(\frac{dX}{dt}\right)_{\Delta t} = \frac{(X_3 - X_{\Delta t})}{(t_3 + \Delta t)} \tag{13}$$

and the nowcast of X at time t due to $X_{\Delta t}$ is calculated as

$$X_t^{'} = X_{\Delta t} + \beta \bullet \left(\frac{dX}{dt}\right)_{\Delta t} \bullet (t + \Delta t). \tag{14}$$

If both X_t and $X_t^{'}$ values are available, the new nowcast value of X at time t is calculated as

$$X = \frac{w_t X_t + w' X'_t}{w_t + w'}, \tag{15}$$

where

w_t and w' are weighting factors defined as

$$w_t = \frac{1}{t - t_0} \tag{16}$$

and

$$w' = \frac{1}{t + \Delta t}. \tag{17}$$

In practice, Δt is limited to less than 3 h. If previous nowcast fields are 3 h or older than the current desired WRE-N time t_0, they are not used. An empirical parameter β is used to adjust the time rate of change of X in equations 2 and 4. In section 6, reasonable values for β will be investigated.

5. Computer Programs and Input Files

The present WRE-N is composed of the following FORTRAN 77 program and sub-programs:

1. *nowcast_main.f*: This is the main module that reads MM5, upper-air radiosonde sounding data, and terrain data. The subroutines *3dobj.f*, *3dobj_dpt.f*, *3dobj_ncomp.f*, and *nowcast_imets.f* are called from within this program. After upper-air and surface objective analyses of meteorological data are executed (and merged using MARIAH similarity theory) for times t_0 and t_3 (discussed in section 3), nowcast calculations are then produced as discussed in section 4. An output file *short_range_fcst_file* is produced upon completion of this program, representing the final 4D WRE-N grid.
2. *3dobj.f*: This subroutine is used when no upper-air radiosonde sounding data are available. The MM5 forecast data are three-dimensionally analyzed onto grid points of the WRE-N for times t_0 and t_3.
3. *3dobj_dpt.f* and *3dobj_ncomp.f*: When upper-air radiosonde sounding data are available within the WRE-N time and space domain, the MM5 forecast data are composed with the observed upper-air radiosonde data (discussed in section 3). These programs are used only for time t_0.
4. *nowcast_imets.f*: The observed surface meteorological data are objectively analyzed with a successive correction method (discussed in section 3) using the data analyzed by *3dobj*.f or *3dobj_dpt.f/3dobj_ncomp.f* as background data, and are subject to the MARIAH similarity formulas.

To use as much observed data as possible per WRE-N cycle, all surface observation data observed within ± 30 min of t_0 and all upper-air radiosonde sounding data taken within 2 hr of t_0, are used. Only gross quality control measures are used at this time, and currently no special weighting is used to differentiate between ingest data of different ages. The present scheme is designed to cycle at hourly intervals, although 30-min cycling is possible. Also, the present configuration of the WRE-N produces output fields at 30-min intervals out to 3 h.

5.1 Examples of the WRE-N

In this section, a WRE-N example valid at 0000 Universal Time Coordinated (UTC), 10 May 2005 for the previously described Dallas domain is shown. Figure 5 shows the 15-km resolution MM5 horizontal wind vector distribution at the 10-m level for 0000 UTC, 10 May 2005, prior to interpolation onto the finer-resolution WRE-N grid.

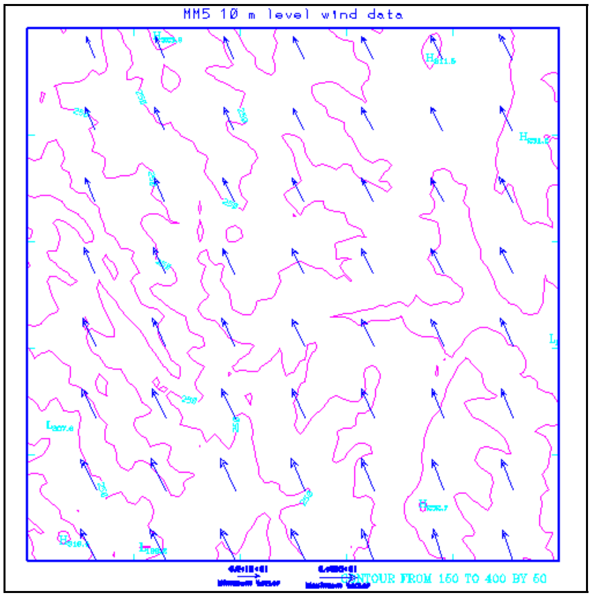

Figure 5. MM5 grid horizontal surface wind vector distribution at 10 magl for 0000 UTC, 10 May 2005.

Figure 6 is the 15-km resolution MM5 horizontal wind vector distribution at the 10-magl level, after interpolation onto the finer-resolution 1.5-km WRE-N grid for the Dallas domain. In this figure, for graphical clarity, vectors are drawn only at every other grid point. Observed surface wind vectors at the same valid time are shown in figure 7.

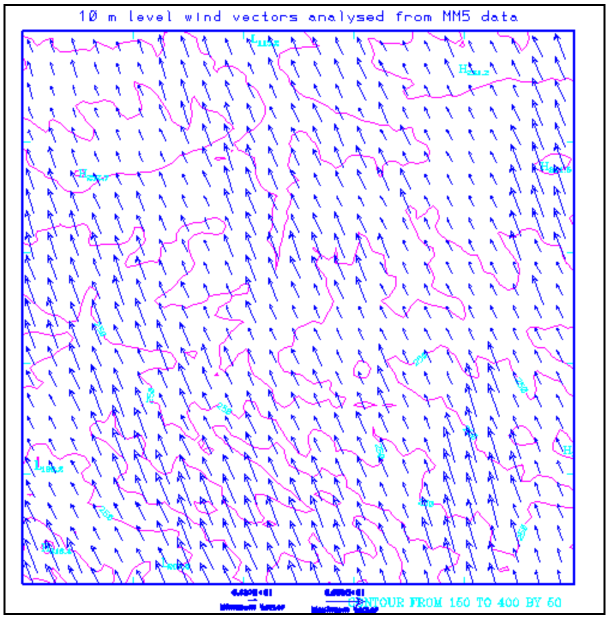

Figure 6. The 10-magl horizontal surface wind vector distribution interpolated from the MM5 grid to the WRE-N grid for 0000 UTC, 10 May 2005.

NOTE: For clarity, only vectors at every other grid point are drawn.

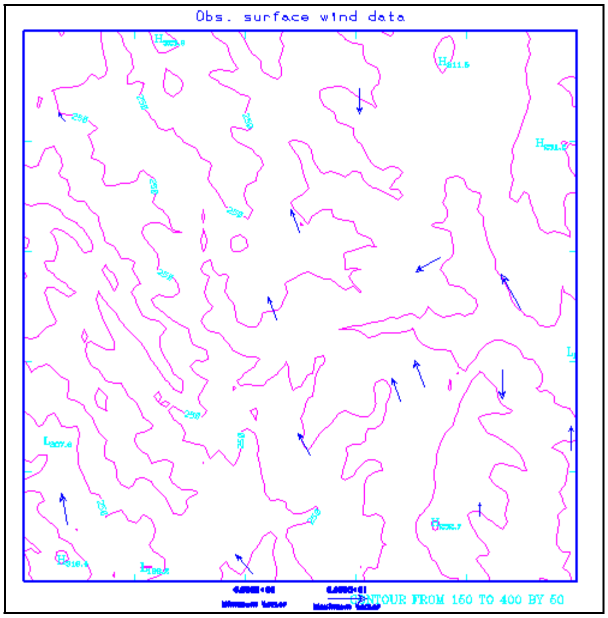

Figure 7. Observed 10-magl surface wind vectors valid at 0000 UTC, 10 May 2005.

Maximum and minimum wind speeds obtained from just the interpolated 15-km resolution MM5 forecast data for this case are 6.9 and 1.5 m/s, respectively. Figure 8 shows the time t_0 WRE 10-magl surface wind field, valid for 0000 UTC, 10 May 2005, obtained after the various successive correction analyses and similarity theory calculations (to merge the upper-air and surface analyses) were executed. Maximum and minimum wind speeds of the WRE wind fields are increased from those obtained solely from the MM5to 8.9 and 2.3 m/s, respectively. Notice that the WRE wind directions are also modified. Figure 9 shows the 2 h (t_0 + 2 h) nowcast 10-magl surface level wind field valid at 0200 UTC, 10 May 2005, based on the WRE wind field (t_0) shown in figure 8 (discussed in section 4).

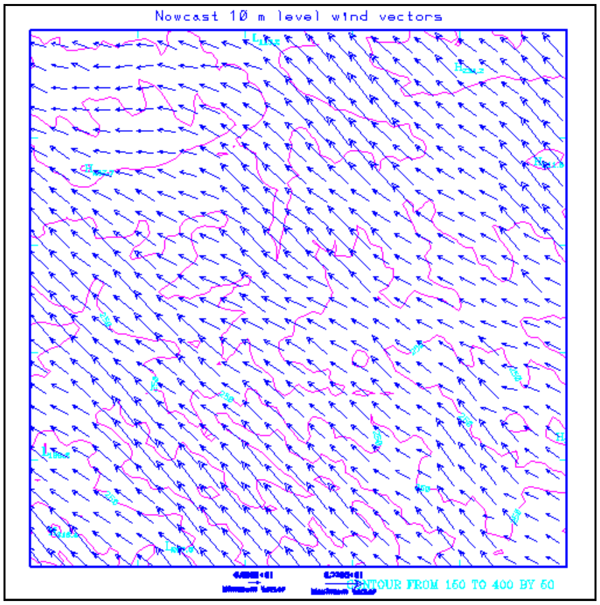

Figure 8. The 10-magl surface wind field produced by the WRE-N analysis module (0000 UTC, 10 May 2005), by combining the fields shown in figures 6 and 7.

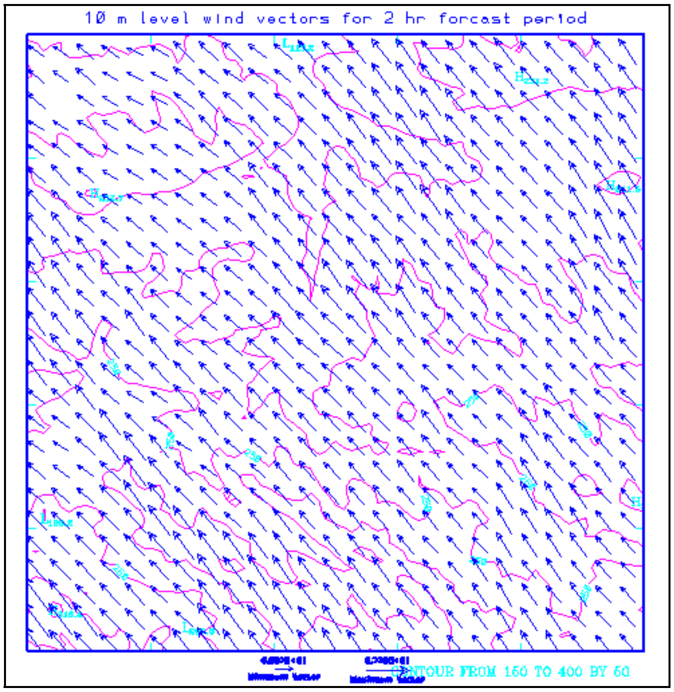

Figure 9. The 10 magl surface wind field valid for 0200 UTC, 10 May 2005, the 2-h gridded nowcast produced by the WRE-N extrapolation module.

The 2-magl level surface temperature field generated purely from the 15-km MM5 forecast data is shown in figure 10. For this temperature field, the maximum and minimum temperatures were 32.8 and 30.3 °C, respectively. Figure 11 shows the 2-magl level surface temperature field after the execution of all the analysis steps necessary to produce the t_0 WRE. The 2-magl level surface WRE temperature field has both maximum and minimum temperatures decreasing to 27.0 and 22.5 °C, respectively. This is more than 5 ºC lower than temperatures predicted by the operational AFWA MM5 15-km resolution forecasts.

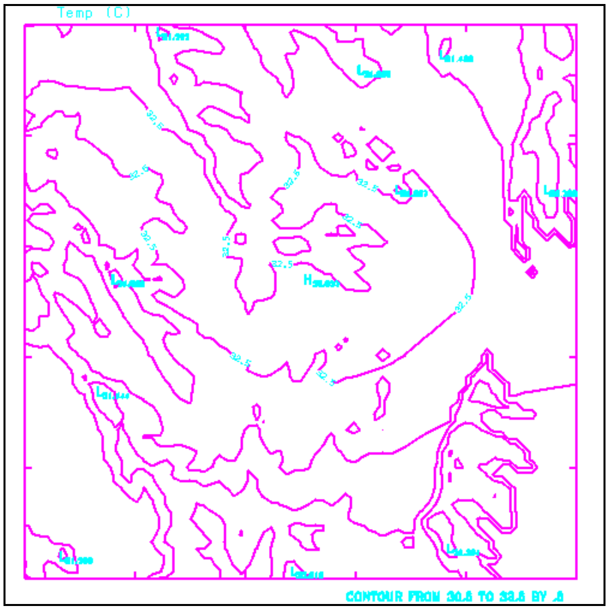

Figure 10. The 2-magl surface temperature distribution from the MM5 interpolated to the WRE-N grid, valid at 0000 UTC, 10 May 2005.

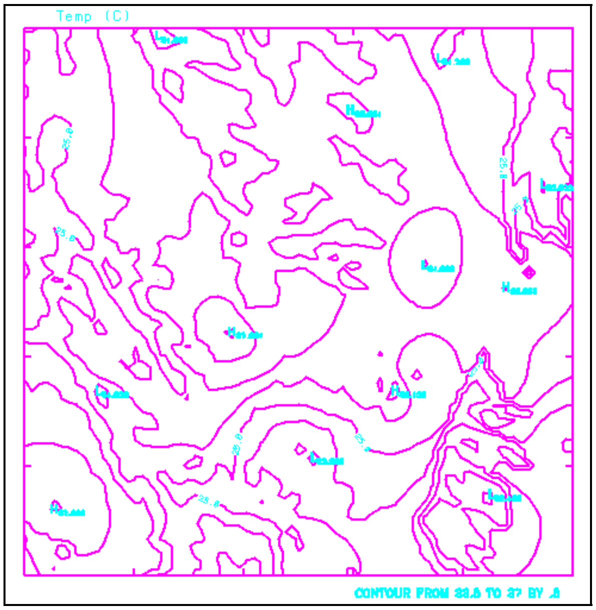

Figure 11. The 2-magl surface temperature field produced by the WRE-N analysis module by combining the temperature field shown in figure 10 with observations valid for 00 UTC, 10 May 2005.

Figure 12 shows vertical distributions (valid at 0000 UTC, 10 May 2005) at the KFWD (Fort Worth, TX) radiosonde site for temperature and dew-point temperature. Three vertical profiles are plotted, generated from the original 15-km resolution MM5 forecast, the raw upper-air radiosonde sounding observation, and the WRE. The vertical profiles of wind speed and wind direction for the same location and time are shown in figure 13.

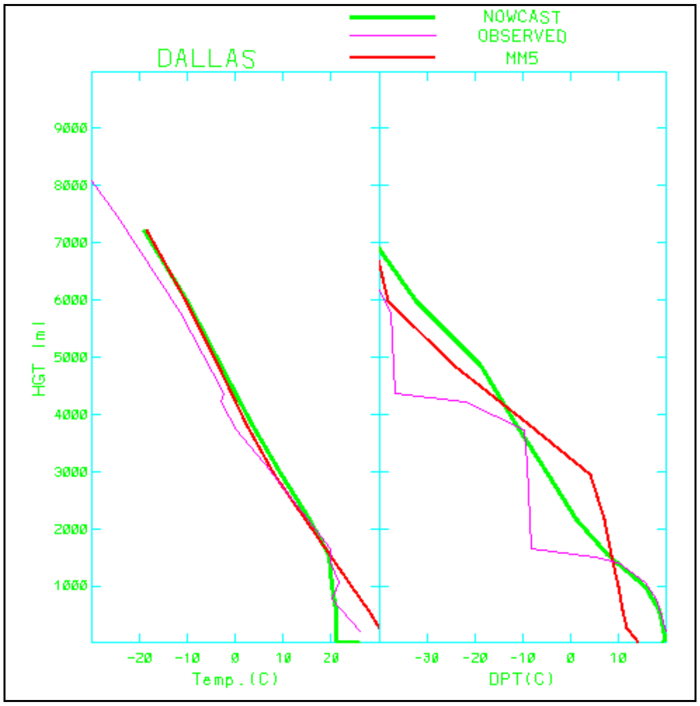

Figure 12. Vertical profiles of temperature and dew-point temperature valid for the KFWD (Fort Worth, TX) radiosonde site at 0000 UTC, 10 May 2005. Profiles produced by the AFWA MM5, the KFWD radiosonde, and the WRE-N analysis module are shown.

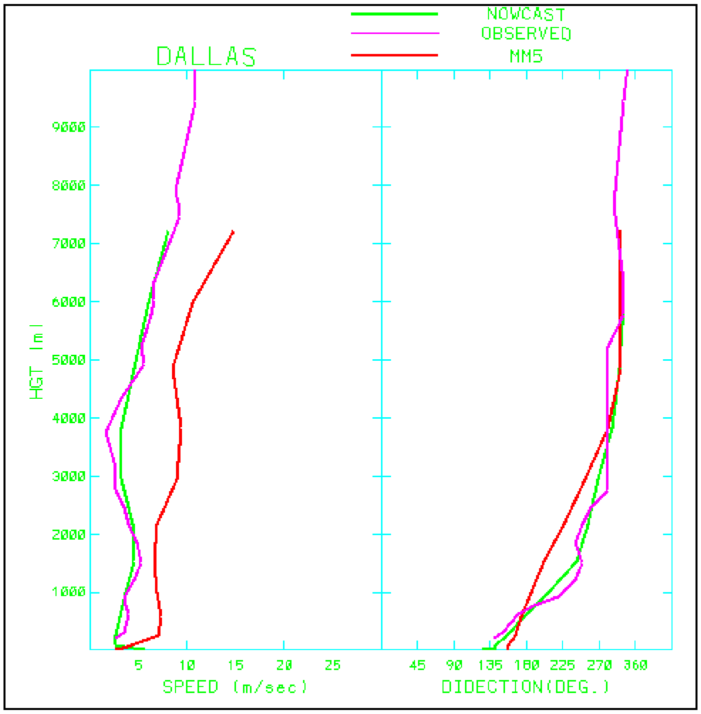

Figure 13. Same as figure 12, except for wind speed and wind direction.

5.2 Preliminary Evaluation of the WRE-N Method

All 15-km resolution MM5 data, hourly surface observation data, and upper-air radiosonde sounding data were collected over the Dallas domain shown in figure 3 for the period from 16 April–12 May 2005. In this 111 km-by-111 km area (75-by-75 grid points with a 1.5-km grid resolution), there are 16 regularly reporting surface stations.

Similar datasets were collected for the period from 16 May–25 May 2005 over the Denver domain shown in figure 14, covering an area of 248 km by 248 km (125-by-125 grid points with a 2-km grid resolution) centered at 39.5° N. and 104.1° W. There are only 12 surface stations within this domain, all over the plains area to the east of the Rocky Mountain frontal range.

Since there are only a limited number of surface and upper-air radiosonde stations available in both domains, all the observations are used for producing the WRE analyses at time t_0 (0 h). In the remainder of this section, all available surface observations are also used to evaluate the quality of the WRE-N fields at times t_0, t_0+1 h, t_0+2 h, and t_0+3 h. Temperature and dew-point are evaluated at the 2-magl level, and winds are evaluated at the 10-magl level. Statistical parameters, such as mean absolute difference (AD) and correlation coefficient (CC), are calculated at each WRE-N time period for the parameters of temperature, dew-point temperature, and wind speed. Root mean square vector error (RMSVE) and mean wind direction difference (MWDDF) are also calculated for the horizontal wind vector. These statistical parameters are described in Henmi (2002).

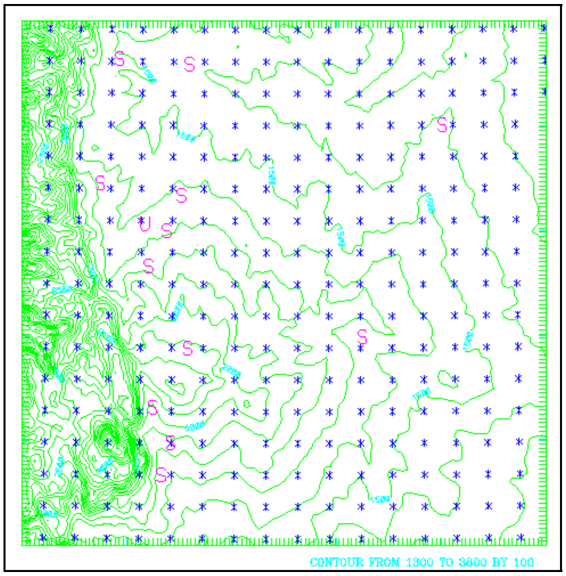

Figure 14. Terrain contour distribution for the 125-by-125 domain of 2-km grid spacing, centered at 39.5° N. and 104.1° W. (Denver domain).

NOTE: The “*” symbol represents MM5 grid points, and the “S” and “U” symbols represent the locations of the surface and upper-air radiosonde meteorological observations, respectively.

WRE-N calculations with different values of β (0.0, 0.2, 0.4, 0.6, 0.8, and 1.0), along with WRE-N produced with no observation data (MM5 data interpolation), are compared with observations for the surface fields. A β-value of 0.0 represents persistence. On the other hand, a β-value of 1.0 represents total reliance on the pure AFWA MM5 forecast at the end period (t_0 + 3 h).

Figures 15 and 16 show the time series of AD and CC for surface temperature for both the Dallas and Denver domains, respectively. For the Dallas domain, the current WRE-N method produced better statistics than relying solely on the existing AFWA MM5 forecasts for up to 3 h forward from the WRE time t_0. However, for the complex terrain of the Denver domain, at the WRE-N time of t_0+3 h, the statistics of the AFWA MM5 exceeded those obtained by the current WRE-N method (for all β-values tested). For the Denver domain, the current WRE-N method produced better statistics than those from the AFWA MM5 up until t_0+2 h. It should also be noted that the statistics for surface temperature produced from the AFWA MM5 over the Denver domain are better than those produced over the Dallas domain.

Figures 17 and 18 are similar to figures 15 and 16, except they show surface dew-point temperature. For the Dallas domain, a persistence forecast (β = 0.0) produced the best statistics and a β = 1.0 produced the worst statistics, indicating that over this domain dew-point temperature changes slowly with time (and may not be forecasted well by the AFWA MM5). On the contrary, for the Denver domain, the best surface dew-point temperature statistics were obtained with a β = 1.0. Over the Dallas domain, the present WRE-N method could be statistically better than the pure AFWA MM5 forecast up to t_0+ 3 h, but over the Denver domain, the same WRE-N method was statistically better than the AFWA MM5 only out to t_0+ 2 h.

Figures 19 and 20 display similar statistics for wind speed. It is noted that the surface wind speed statistics of the AFWA MM5 forecasts over the Denver domain are better than those produced over the Dallas domain. Over the Dallas domain, the present WRE-N method, with various values of β, yielded better statistics than the AFWA MM5 out to t_0+ 3 h, with β = 0.2 producing the best statistics. This may indicate that wind speed changes slowly with time over this domain and is more uniform in distribution. Over the Denver domain, the method using β = 1.0 produced the best statistics, with β = 0.0 generating the worst statistics for wind speed. Again, this may be a consequence of the surface wind field varying significantly across the Denver domain due to the complex topography, and the AFWA MM5 model may have some skill at predicting/resolving the local diurnal mesoscale wind field.

The RMSVE and MWDDF surface wind field statistics are plotted in figures 21 and 22 for the Dallas and Denver domains, respectively. For wind vectors, the AFWA MM5 forecast is considerably better for the Dallas domain than for the Denver domain. For both domains, the RMSVE and MWDDF statistics generated by the present WRE-N method (with various β values) are smaller than those from just the AFWA MM5 forecasts out to t_0+ 3 h. It can be seen that both the surface wind RMSVE and MWDDF statistics for the Dallas domain are smaller than those for the Denver domain.

From these results, it can be tentatively concluded that, for practical purposes, an appropriate value for β is 0.5. With further study and added complexity, this parameter could be allowed to vary based on a particular meteorological and geographical scenario, though to do so in an automated fashion, without user input, would be challenging.

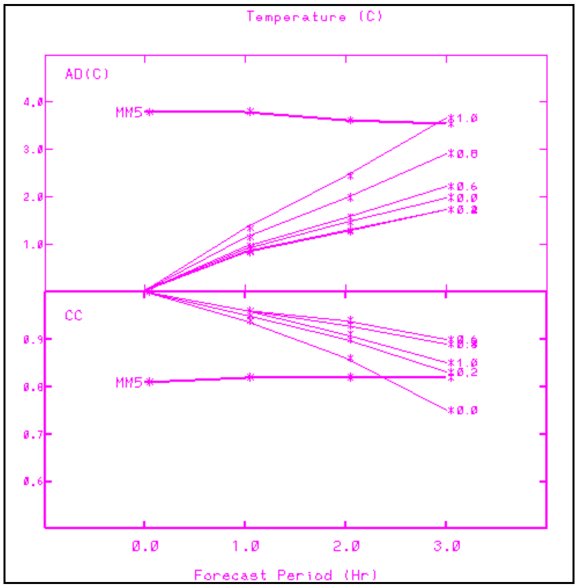

Figure 15. AD and CC of surface temperatures as a function of the WRE-N nowcast period for different β values and for the Dallas domain.

NOTE: The β values are given at the right ends of lines. The line with “MM5” refers to AFWA MM5 forecast data (i.e., the background fields for the WRE-N).

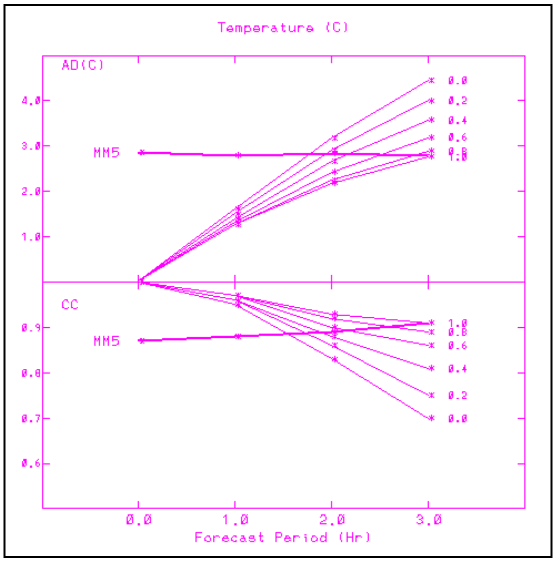

Figure 16. Same as figure 15, except for the Denver domain.

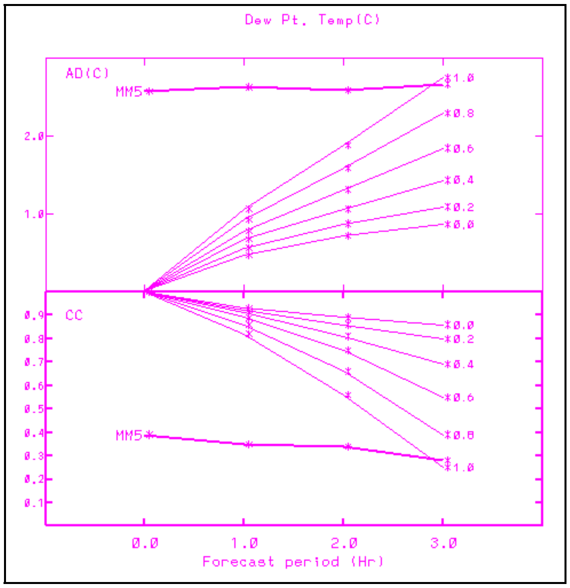

Figure 17. Same as figure 15, except for the dew-point temperature.

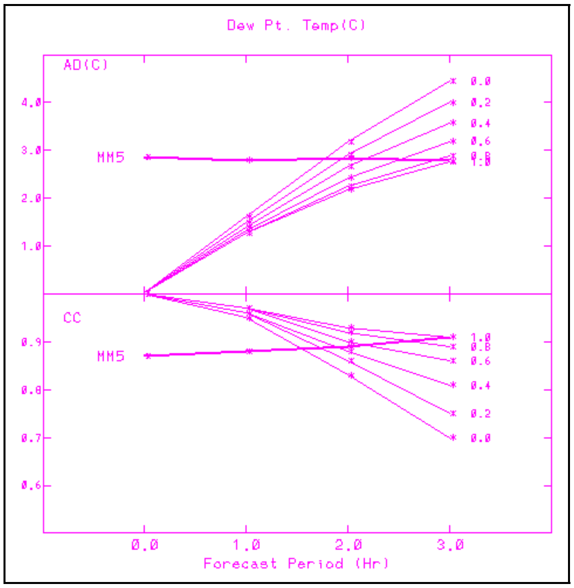

Figure 18. Same as figure 17, except for the Denver domain.

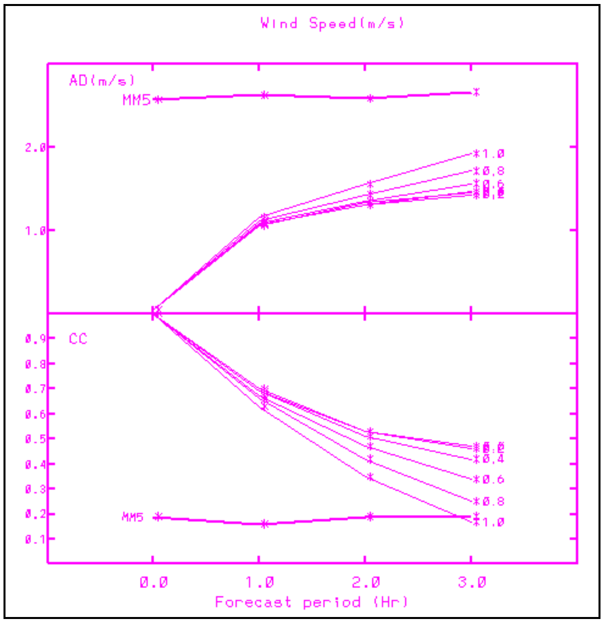

Figure 19. Same as figure 15, except for the wind speed.

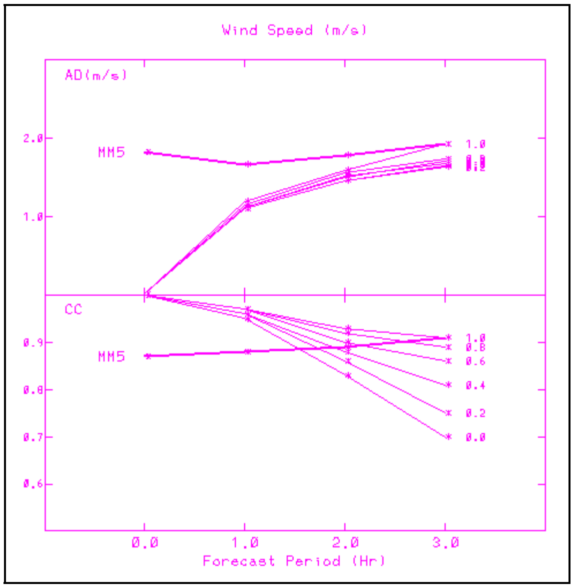

Figure 20. Same as figure 19, except for the Denver domain.

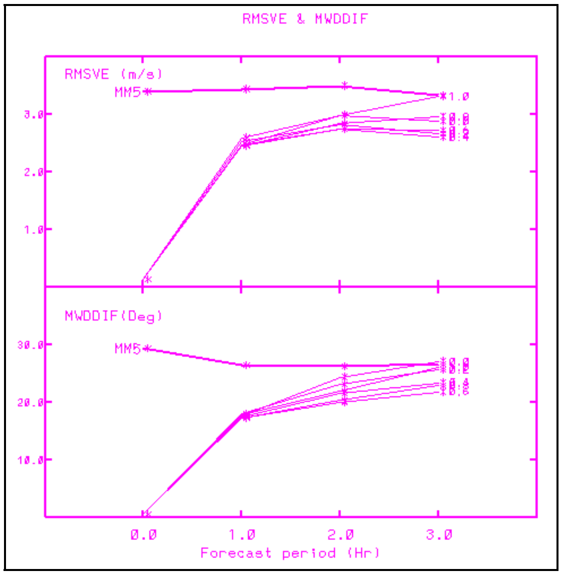

Figure 21. The RMSVE and MWDDF as a function of the WRE-N nowcast period for the Dallas domain.

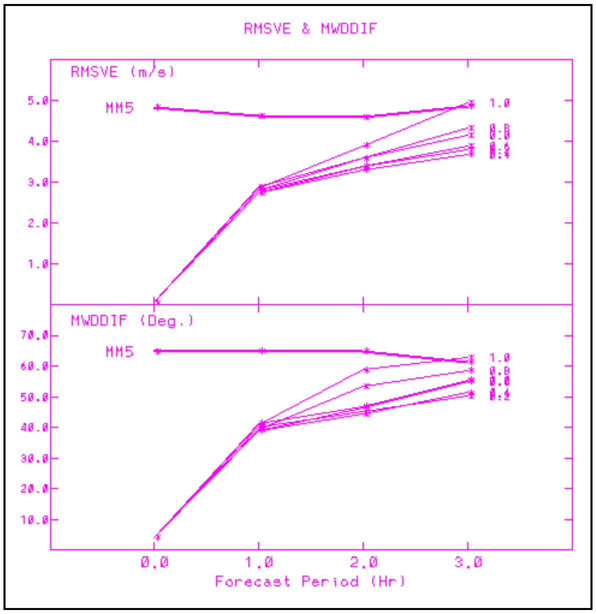

Figure 22. Same as figure 21, except for the Denver domain.

8. Conclusion

An initial WRE-N method for the IMETS has been developed, discussed, and evaluated. In the present method, meteorological parameters including temperature, dew-point temperature, and *u* and *v* horizontal wind vector components (and surface pressure, although it was not discussed) are analyzed and nowcasted. At first, the 3D fields are computed across the entire WRE-N 3D grid for each meteorological parameter (arbitrarily represented by X_0 and X_3) at times t_0 and t_0 + 3 h, respectively. The nowcast of these parameters, at times between t_0 and t_0 + 3 h, are done under the assumption that these parameters change linearly with the time rate of change, multiplied by an empirical parameter β. Additionally, in cases where a WRE-N parameter field ($X_{\Delta t}$) calculated from a previous time Δt (less than 3 h prior to t_0) exists, the WRE-N is based on X_0, X_3, and $X_{\Delta t}$. Only the most recent WRE-N field prior to the t_0 is used in the calculations.

This method has been applied to two different areas centered near Dallas, TX, and Denver, CO, and has been evaluated using surface observation data from the spring of 2005. It was shown that an appropriate value for the empirical parameter β varies between meteorological parameters and different domains. An appropriate value for β was tentatively determined as 0.5, although the statistical evaluation studies described in this report are based on the comparison between WRE-N values and observation for only limited seasonal periods and geographical areas. This evaluation study was done only for cases where a previous WRE-N field was not used to generate a new WRE-N. Further studies are needed to evaluate the present method for cases in which previous WRE-N fields are utilized. The present forecast method was shown valid up to 3 h over the Dallas domain, and up to 2 h over the Denver domain. Again, tentatively, we conclude the method can be valid for producing a 2- or 3-h WRE-N, adding some value over relying on the existing background AFWA 15-km MM5 forecast data alone.

Because there is no physical and dynamic coupling of the WRE analysis to an NWP model when producing the current WRE-N fields, certain meteorological situations (such as those with fast moving meso/micro boundaries and thunderstorm gust fronts) will pose significant difficulty unless the AFWA MM5 forecast can capture these features accurately in time and space. To address this problem (as well as to provide a capability to ingest many other types of non-conventional meteorological observations), a more sophisticated WRE-N is being envisioned for the Distributed Common Ground Station–Army (DGCS–A) for development later this decade. The approach being developed is based on diabatic initialization and would be a fully coupled analysis and NWP assimilation system. At this time, a LAPS (Shaw et al., 2004) and WRF (Skamarock et al., 2005) coupled system is being investigated for application as this advanced WRE-N.

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Acronyms

3D	three-dimensional
AFWA	Air Force Weather Agency
AOI	area of interest
ARL	U.S. Army Research Laboratory
CC	Correlation Coefficient
DGCS–A	Distributed Common Ground Station–Army
DMA	Defense Mapping Agency
DTED	Digital Terrain Elevation Data
GRIB	gridded binary
IMETS	Integrated Meteorological System
MM5	Mesoscale Model Version 5
MWDDF	Mean Wind Direction Difference
NWP	Numerical Weather Prediction
RMSVE	Root Mean Square Vector Error
UTC	Universal Time Coordinated
UTM	Universal Transversal Mercator
WMO	World Meteorological Organization
WRE	Weather Running Estimate
WRE-N	Weather Running Estimate-Nowcast

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