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Vertical Extrapolation Model and Next Generation Radiometer Profile Comparisons and Artillery Accuracy

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13. ABSTRACT (Maximum 200 words)

A comparison of the Vertical Extrapolation Model (VEM) and the Next Generation Radiometer (NGR) is presented in terms of the accuracy of their output temperature and density profiles, as well as how these profiles impact simulated artillery firings accuracy. The VEM is a software package that outputs a computer meteorological message containing wind direction, wind speed, virtual temperature, and pressure. The NGR is a component of the Meteorological Measuring Set - Prototype (MMS-P) profiler system being developed by the U. S. Army Research Laboratory (ARL) to measure temperature, wind, and atmospheric moisture using a variety of surface and satellite-based instruments. Simulated 155-mm Howitzer artillery firings were carried out at three ranges: 15, 20, and 22 km. Only virtual temperature and density effects were considered in these simulations and when all simulated results were averaged , the NGR output data always allowed the projectile to land within 38 m of the target. The VEM options allowed the projectile to land within 49 m of the target when firing at the 15 km range.

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Executive Summary

This study compares the accuracy of the Vertical Extrapolation Model (VEM) and the Next Generation Radiometer (NGR) temperature profiles estimating radiosonde temperature measurements. The VEM is a software package onboard the Semiautomatic Meteorological Station (SMS) (Environmental Technologies Group, Inc., 1997). Using surface observations, the VEM calculates wind direction, wind speed, virtual temperature, and pressure profiles. NGR is a microwave radiometer that deduces temperature profiles and atmospheric liquid water and water vapor based on the thermal radiation of the atmosphere. Pressure profiles are inferred indirectly using the hypsometric equation and a surface pressure measurement along with the NGR-derived temperature profile.

To produce temperature profiles, the VEM extrapolates surface temperatures while the NGR is a remote sensing system. Intuitively then, NGR should produce a more accurate temperature profile, particularly with increasing height. Yet, the NGR requires predetermined regression coefficients based on a particular climatic regime. VEM, on the other hand, is simply a software package requiring inputs of surface meteorological (met) parameters. Making the assumption that VEM could provide reasonably accurate temperature data at lower levels, this report endeavored to see at what height level(s) the simpler and less expensive VEM system could compete with NGR in terms of how its output data could provide for accurate simulated artillery firings.

A database of 15 radiosonde launches and simultaneous NGR measurements taken from Dec 96 to Jan 97 provided the basis for this study comparing the accuracy of VEM and NGR.

Over the 15 time periods comprising this study, NGR estimated virtual temperature profiles more accurately than VEM by about 3.5 °C.

The 155-mm Howitzer firings were simulated for ranges of 15, 20, and 22 km. The results for different effects, such as temperature and density, were calculated and averaged over the 15 time periods. When the individual root mean square miss errors (rmse) for temperature and density were averaged, NGR data always put the projectile closer to the target, and in fact, always put it within 39 m of the target. The VEM data allowed the projectile to land within 49 m at a 15-km range. The apogee for a 15-km shot is 1 km; being within the lethal radius for a 1-km apogee firing, confirmed the authors' premise that VEM could provide reasonably accurate temperature data at lower levels.

Based on the temperature and density comparisons, the VEM can be an effective estimator for short range targets (<15 km) typically encountered by the light forces.

1. Introduction

In a battlefield situation, meteorological (met) sections are deployed to gather the latest weather information including surface measurements and upper air (balloon) soundings. This data is formatted into a 26 line (accounting for the atmospheric layer from the surface to 20 km above ground level [AGL]) met message, which is passed to the fire controls where it is used to make aiming adjustments for the artillery. This report will refer to 9 line met messages throughout because this is what VEM outputs. These met sections employ the Meteorological Measuring Set (MMS) to obtain upper air soundings.

There is the potential that early in a conflict, an MMS would not be available. However, fire control will still require computer met messages to make aiming adjustments for the artillery. By running the Vertical Extrapolation Model (VEM) onboard the Semiautomatic Meteorological System (SMS), this need can be satisfied until an MMS is available.

The use of weather balloons on the battlefield presents certain problems. First, hydrogen must be generated for inflation. After donning a chemical suit, the soldier places chemicals into a hydrogen generator. This is not only time consuming (and potentially explosive), but also cumbersome since the chemical holding canisters constitute additional freight. Also, unless winds are calm for a 4-km height, the balloon will drift and the data from higher levels may be several kilometers removed from the balloon launch site. To address these problems, a new MMS is being developed called the MMS Prototype Profiler (MMS-P). MMS-P will eliminate the need for weather balloons by:

- using the NGR for measuring temperature at lower levels and satellite sounding data at higher levels, and
- measuring winds using a combination of radar and satellite measurements.

1.1 VEM

The VEM is a software package installed on the MMS (AN/TMQ-41) and SMS (AN/TMQ-50). The SMS is a portable military met station. The SMS has a 24- by 3.5-in. diameter container with a hand-held control unit. The VEM provides vertical profiles of wind direction, wind speed, virtual temperature, and pressure given estimates of the expected minimum and maximum temperatures, current surface temperature, relative humidity, pressure, wind direction, and wind speed plus cloud cover and cloud height. When there has been a previous balloon sounding, a bias adjustment can be made to the VEM temperature profile. This bias adjustment is simply a translation of the entire temperature profile. Also, with a previous sounding, a wind measurement at a higher height will now be available. This information can be incorporated to improve the VEM wind profile. The VEM is currently being included in the MMS Value Engineering Change to provide an improved Visual Computer Met Message. [1]

1.2 NGR

The Next Generation Radiometer (NGR) is a microwave radiometer that determines temperature profiles and concentrations of atmospheric liquid water and water vapor based on the natural emissions of atmospheric oxygen and water. Using measured radiances and regression coefficients computed from a database of radiosonde observations (raob), the NGR deduces atmospheric temperature profiles. Using a surface pressure measurement together with an NGR derived temperature profile, a pressure profile can be calculated using the hypsometric equation.

1.3 Purpose

This study was undertaken to determine if there were some height levels where the accuracy of the surface temperature extrapolation software, VEM, could compete with the accuracy of the measurement system, NGR. Certainly, the measurement system will be more accurate overall. Can the VEM (which requires no advanced regional tuning) provide temperature data at lower levels that is accurate enough to warrant its use in short range artillery firings? This report presents data in terms of simulated 155-mm Howitzer firings and in terms of one-on-one temperature profile comparisons to help answer this question.

2. Theory of Operation

2.1 VEM

The VEM uses a particular cosine solution to the partial differential equation for diffusion of heat. This temperature profile solution is a function of height above the surface (z) and time of day (t).

$$T(z,t) = T(z_{ref},t) + \Gamma\Delta z + \Delta T(z,t) \quad (1)$$

where Γ is the adiabatic lapse rate, z_{ref} is the reference height, typically 2 m, and ΔT is the particular cosine solution:

$$\Delta T(z,t) = A\exp(-az)\cos(2\Pi t / 24 - az) \quad (2)$$

where A is the amplitude of the surface temperature wave and a is the partial differential equation separation constant (positive multiple of Π). The relevant equations are:

$$A = (T_{\max} - T_{\min}) / 2 \quad (3)$$

$$a = \sqrt{\Pi / (24 * K_h * 3600)} \quad (4)$$

where

$$K_h = 3 * K_m \quad (5)$$

and

$$K_m(z) = K_t + ((Z - Z_t) / (Z_t - Z_b))**2 * [K_b - K_t + (z - z_b) * [(\partial K / \partial z)_b + 2 * (K_b - K_t) / (z_t - z_b)]] \quad (6)$$

z_t = the top of the friction layer (taken to be 1400 m here);
z_b = refers to the base level where K_m and $\partial Km/\partial z$ have been determined;
K_h = the heat exchange coefficient;
K_m = the momentum exchange coefficient and is calculated in Eq. (6) by O'Brien's formula;

K_t = the eddy exchange coefficient of momentum at the top of the friction layer (in this particular case, it is set to 0, but could be set to a small value); and

K_b = the eddy exchange coefficient of momentum at the bottom of the friction layer (0.25 m^2/s).

From this particular solution, "temperature adjustment," $\Delta T(z,t)$, is derived and is applied to a standard atmosphere temperature profile that has been adjusted to the local elevation. This temperature adjustment is applied to create a temperature profile that is reflective of the current state of the atmosphere (stable, neutral, or unstable) at particular levels. Within VEM, there is a stability classification module that is based on the Pasquill categorization. The Pasquill category output from this module is used for two purposes within VEM:

- to apply the temperature adjustment to the profile so that the profile reflects the current state of the atmosphere and

- to select the correct exponent for extrapolating the surface wind speed. For a detailed examination of the theory behind VEM and a description of the main software modules, refer to *An Improved Visual Computer Meteorological Message*. [1]

The VEM has two options for the bias correction: a "built-in bias," which always applies, and a "bias adjustment" which applies when there has been a previous raob launch. In comparing plots of VEM estimates versus the actual profiles, Kirby and Blanco have found that the VEM [Eq. (1)] typically underestimates temperature. This is apparently because the VEM cosine solution assumes a 12-h period between min and max temperatures that is generally not the case. In a previous study using micrometeorological data taken during an Australian winter, a built-in bias of 2.0 °C was found to be appropriate. This has the effect of translating the entire VEM estimate profile 2 °C to the right.

When there is no raob launch in a day, this built-in bias comes into play. In situations where a raob launch is available in a day, the bias adjustment can be computed. If the built-in bias is adequate, the bias adjustment can be 0; however, in many cases this will not be true. For example, suppose the first raob launch of the day is at 0600 h LT. The user will run the VEM for this time by inputting the appropriate surface temperature, min and max temperatures, relative humidity, pressure, wind information, as well as the cloud cover and ceiling (if any). Cloud information along with winds are parameters required for determining the stability classification. If much of the VEM temperature profile was 4 °C cooler than truth (the raob), a bias adjustment of +4 °C should be used on subsequent VEM runs until another raob can be launched and another bias adjustment determined.

Figure 1 is a plot of the VEM (the <> symbol) and the raob (the + symbol) virtual temperature for 12 Dec 96, 21 Z. The min and max temperatures input to the VEM were the previous day's min and max, 7.80 °C and 21.70 °C respectively. So VEM calculates Tmean = (7.80 + 21.70)/2 = 14.75. The standard adiabatic lapse rate is used to extrapolate a temperature profile from the Tmean (dotted curve). The built-in bias (+2 °C) is now added to derive the initial VEM profile estimate. The adjustment described in Eq. (2) is then applied to compute the final VEM profile.

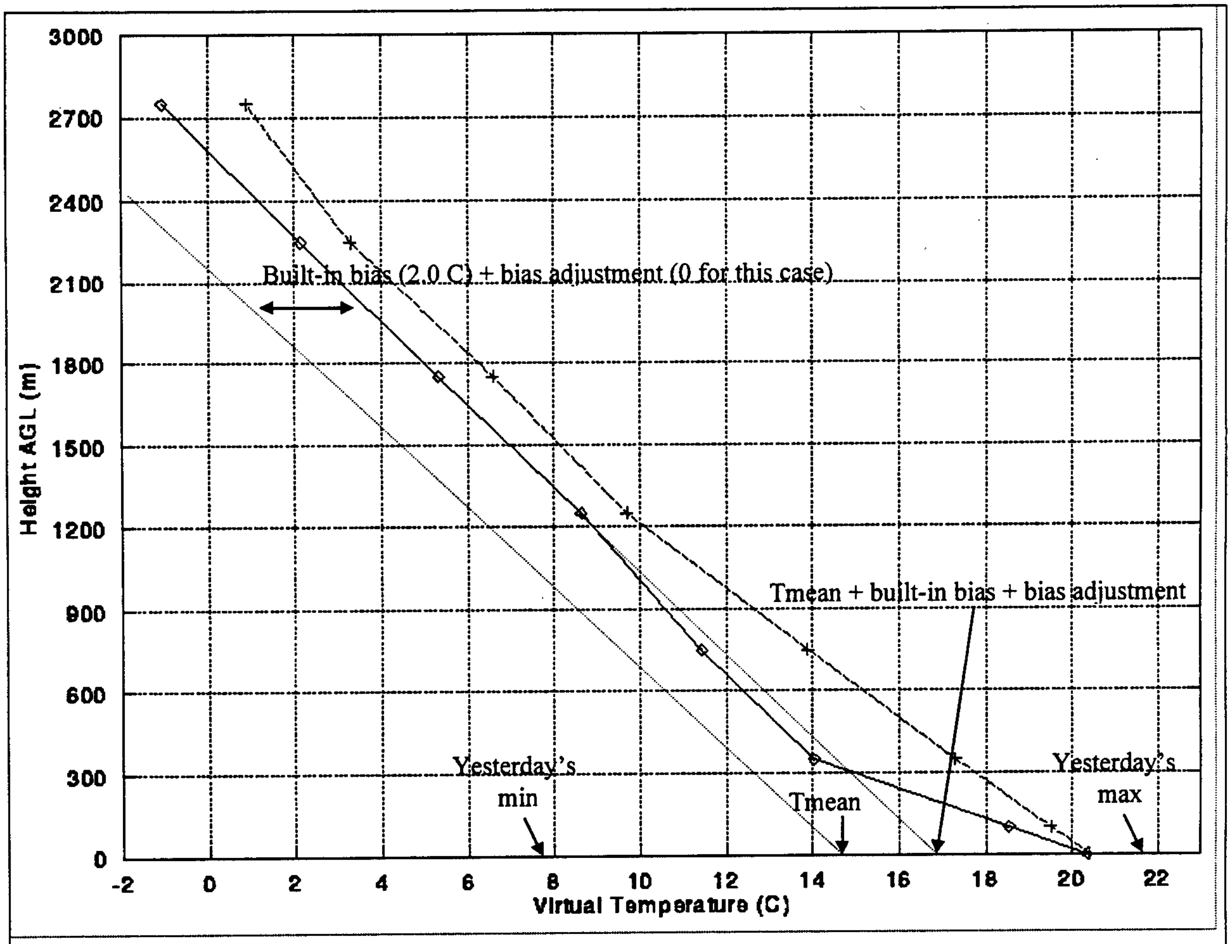


Figure 1. An illustration of the 2 biases used in VEM; VEM = <>; raob = +;

As one follows a VEM profile up, notice that it asymptotically approaches the standard atmosphere temperature profile (adjusted for elevation). This is because at each computer zone midpoint, a temperature adjustment is added to the standard atmosphere value and the magnitude of the temperature adjustment value decreases with height. So, one can place a straight edge along the upper portion of the VEM profile and trace down to where it intersects the x-axis. This intersection point is Tmean + built-in bias + bias adjustment (14.75 + 2.00 + 0 = 16.75). In this particular example, the bias adjustment must be 0 because there is no previous sounding.

One realizes that when VEM is used in the field, it is likely that the capability to visually compare graphs in order to estimate a bias adjustment will be unavailable. Instead, the following is recommended. When there is a previous raob launch one cannot only determine a bias adjustment but also a p value to extrapolate winds from the power law. The user will be asked to input a wind speed and direction at some height. Determining at which height to do this depends on the difference in one's met datum plane and the datum plane of the balloon release site. For example, if this difference is between -500 and 750 m, then the operator will input wind information from line 3 or the 750-m level. It is recommended that the operator also use this level to determine the temperature bias as well. In other words, use the same level for the winds for the bias calculation. This was the method used to determine the bias adjustment for this report.

2.2 NGR

The NGR microwave radiometer is housed in a mailbox-shaped container 29.7 by 18.7 by 9.4 in. It consists of water vapor and oxygen radiometers that share a common elevation mirror and dual feed Gaussian optical antenna. The water vapor subsystem receives at 23.8 GHz (K band) and 31.4 GHz (Ka band), while the oxygen subsystem receives selected channels between 52.8 and 58.8 GHz (V band). [3]

The NGR microwave radiometer exploits the natural thermal radiation of the atmosphere to determine its temperature, composition, and other physical parameters. Most of the radiation received by the radiometers in question can be classified either as scattered radiation (for example, sunlight scattered from cloud droplets, or as thermal radiation); that is, radiation emitted by the volume under consideration and governed by the radiation law:

$$I_\nu = \alpha_\nu B_\nu[T] \qquad (7)$$

where I_ν is the specific intensity of the radiation at frequency ν, α_ν is the absorption coefficient, T is the temperature, and B_ν is the Planck function, given by:

$$B_\nu = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT}-1} \tag{8}$$

where c is the speed of light, h is Planck's constant, and k is Boltzmann's constant. For the frequencies of operation, we can usually neglect nonthermal radiation, so local thermodynamic equilibrium (LTE) applies, and the radiation received by the radiometer is given by:

$$I_\nu = I_\nu^{sc}\exp[-\tau(0,sc)] + \int_0^{sc}\alpha_\nu(s)B_\nu[T(s)]\exp[-\tau(0,s)]ds \tag{9}$$

where s is the distance from the radiometer, I_ν^{sc} is the specific intensity at a bounding surface at distance sc, and:

$\tau(0,s) = \int_0^s \alpha_\nu(s')ds'$ = the opacity of the atmosphere between the radiometer and the volume at s.

Inferring atmospheric temperature structure from microwave brightness temperature measurements thus becomes the problem of solving (inverting) Eq. (9) to find T(s). A database of past raobs has been used to calculate corresponding received radiances at our operating frequencies. Our temperature profiles are calculated with regression coefficients computed from the database radiances and corresponding radiosonde observations. The absorption coefficient $\alpha_\nu(s)$ in the frequency region of interest is due mainly to oxygen lines (50 to 60 GHz), the water vapor line at 22.235 GHz, and a liquid water continuum measured near 31.4 GHz. Oxygen is well mixed in the atmosphere, so a good a priori estimate of its contribution is possible. In our scheme, water vapor and liquid water are independently measured by radiometric channels near 23.8 and 31.4 GHz.

The received microwave radiation is mixed with the output of oscillators of known frequency and the resulting IF difference frequency signal is measured. [3] These measurements are converted to brightness temperature, from which the atmospheric temperatures are retrieved.

The principal components of the radiometry software are the radiometer control program, the signal processing program, the program for generating temperature profiles from brightness temperatures, and the program for generating retrieval coefficients from the database of raobs. The first three programs are run in realtime on the data-taking platform, using retrieval coefficients generated offline by the fourth program.

3. Method

3.1 Balloon Measurements

The balloon soundings were taken in the vicinity of building 305 at White Sands Missile Range (WSMR), NM, over the period Dec 96 to Jan 97. A total of 15 soundings were made, and their launch times parallel as closely as possible the NGR measurement times. There are both early morning and afternoon soundings showing inversions and afternoon soundings. The tracking system used was the Marwin radiosonde tracking system, which is found on the MMS.

3.2 NGR measurements

The NGR measurements were also taken near building 305 over the same time period.

Since the NGR profile measurements were not at coincident heights with the VEM output, they had to be massaged by a program which uses the mean value theorem to get average values at designated heights (computer zone midpoints). [4]

3.3 VEM Calculations

Before any VEM calculations could be made, the following VEM inputs for the 15 time periods of this study had to be obtained from C-Station, the weather station for WSMR:

- cloud cover,
- cloud height,
- surface temperature,
- surface relative humidity,
- surface barometric pressure,
- surface wind direction,
- surface wind speed, and
- previous day's minimum and maximum temperatures.

With these inputs, VEM could then be run producing a computer met message consisting of nine zones of met data at heights (midpoint levels from surface to 3750 m) relevant to artillery needs.

For this study there were three days, 17, 18, and 19 Dec, in which a bias adjustment could be estimated due to the availability of multiple raob launches. For second and later raob launches, a bias adjustment was the computer met message zone 3: (750-m level raob temperature - 750-m level VEM, Vertical Extrapolation Model enhanced with a temperature bias and second-level wind information from a prior raob [VMP] temperature). The order of the difference here is important so that the translation of the VEM profile is in the right direction. The 750-m level was used because the met datum plane and the datum plane of the raob coincided. Each time there was a new raob launch, a new bias adjustment was determined, added to the previous one, and then used in the next VMP run.

3.4 Statistical Comparison Methods

The root mean square error (rmse) using the raob as truth was the main statistical measuring stick used to determine the quality of the measured NGR temperature profiles versus the calculated VEM temperature profiles. The rmse was calculated in terms of the virtual temperature error through varying heights in the atmosphere and in terms of a simulated target impact displacement (meters) for ranges of 15, 20, and 22 kms. In order to calculate the temperature component portion of the error budget for simulated impacts, the computer met messages from VEM and the profile data from NGR and the radiosonde had to be first converted into an Artillery Ballistic Met Message (FM 6-16). This is the format representing the total expected met effect on cannon and rocket displacement. Data at the computer zones are weighted and summed to give a ballistic message for the specific line. For example, line 3 of the message contains the summed and weighted wind, virtual temperature, and density effects on a projectile passing through zones 1, 2, and 3. Similarly, line 5 represents zones 1 to 5, line 6 represents zones 1 to 6, and so on. When the ballistic met message is used in tandem with the Provisional Firing Table (FT 155-AO-O) Unit Effect Data, the expected impact displacement for a rocket-assisted round can be calculated.

4. Results

4.1 Average Temperature Zones

Table 1 below illustrates the average mean absolute virtual temperature error over the 15 time periods comprising this study. Since atmospheric moisture information was available with the NGR data, it was possible to derive virtual temperatures from the sensible temperatures output by NGR. The line for zone 3 is the average for zones 0, 1, 2, and 3, and the line for zone 5 is the average for zones 0 to 5, etc. In the case of VEM, the mean error reaches 5.0 °C when all nine zones are used, while the radiometer error is smaller, only reaching 1.5 °C for all nine zones. As one can see, the error increases slowly as the number of zones in the calculation increases. The radiometer error is consistently lower than the VEM error. Note under VEM-NGR delta, that if one were to use the VEM/VMP model rather than the NGR radiometer, their error on average through all nine zones would be an additional 3.5 °C.

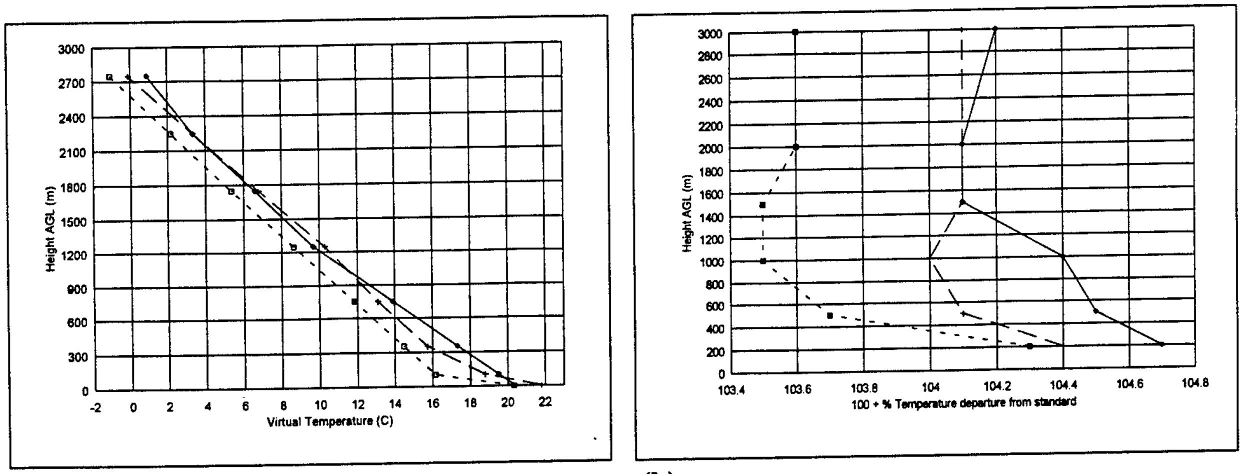
Table 1. The average rmse in virtual temperature (°C) over all 15 time periods through different zones using VEM and VMP and a cumulative bias adjustment

Computer zone	Top (km)	Average rmse VEM	Average rmse NGR	VEM-NGR delta
3	1	2.4	1.4	1.0
5	2	2.9	1.4	1.5
7	3	3.7	1.5	2.2
9	4	5.0	1.5	3.5

4.2 Vertical Temperature Profiles

Figures 2 to 16 represent side-by-side plots of the computer (met message) virtual temperature and the ballistic (met message) percentage departure from a standard atmosphere. The short-dash line (with square symbols) represents the VEM, the longer-dash line (with + symbols) signifies the NGR, and the solid line (with <> symbols) represents the raob. When there was a second raob in a day, a bias adjustment could be used and the resulting VMP profile is signified by the X symbol in the plots. The plots on the left-hand side indicate how accurately VEM and NGR capture the raob temperature profiles. They use information from the computer met message. The right-hand plots in these figures are graphical representations of the ballistic temperature message. In particular, the ballistic met message indicates how the profile's virtual temperature compares to a standard atmosphere's temperature adjusted to the met datum plane (your local elevation). For example, a temperature entry of 014 for line 3 implies the profile's virtual temperature is 1.4 percent higher than the standard atmosphere temperature at a 1-km height. Conversely, an entry of 992 for line 3 implies the virtual temperature is 0.8 percent lower than that of a standard atmosphere profile at 1 km. Note that in the figures, the values plotted are 100 + the percentage departure from standard.

From the data presented on the right-hand side plot, one can determine the expected artillery miss on targets located at different artillery ranges. For example, one can look at the percentage difference between VEM (or NGR) and raob at line 3 (1 km) to determine the range error for artillery being shot 15 km. Then, if one multiplies this difference by the unit effect of 22 m/percentage difference, the miss in the range direction is obtained. Similarly for artillery going 20 km in range, one takes the percentage difference at line 5 (2 km) and multiplies by the unit effect of 30 m/percentage difference. Lastly, for a 22-km range artillery, the percentage difference at line 6 (3 km) times the unit effect of 30 m/percentage difference gives the target miss for that range.



(a) **(b)**

Figure 2. (a) VEM, NGR, and raob virtual temperature; and (b) 100 + % departure from standard atmosphere temperature plots for 12 Dec 96, 21Z. raob = <>; NGR = +; VEM = square.

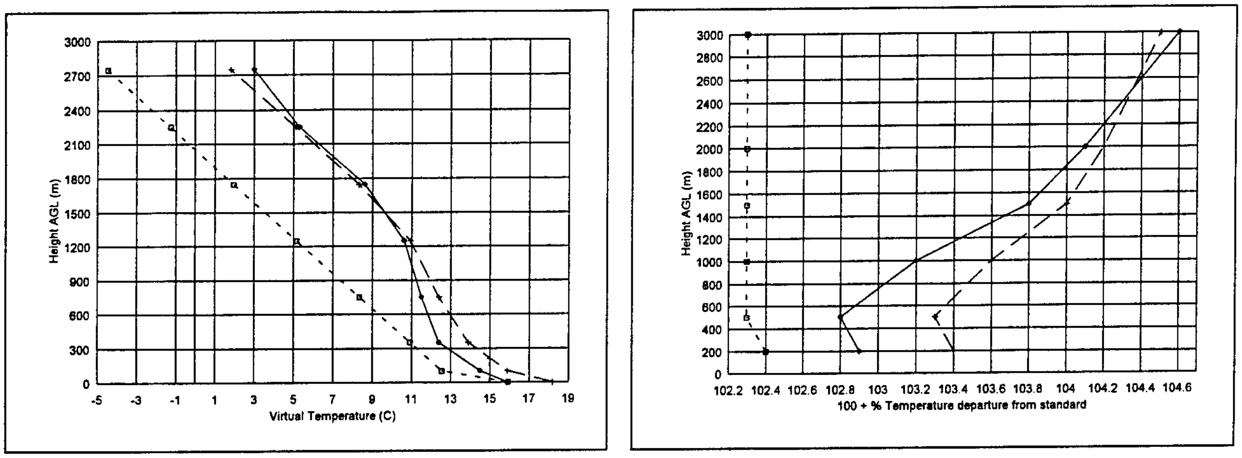
12 Dec 96

2053 GMT

Yesterday's max/min temperature: 21.7/7.8 °C
Today's max/min temperature: 20.6/1.7 °C
Surface wind speed = 2.52 kn
Cloud cover = 0
Ceiling height = not applicable
Pasquill category: B

For 12 Dec 96, figure 2a, the min/max used from the previous day yielded a Tmean which is too low. The built-in bias of 2 °C is not quite large enough, so the VEM profile underestimates the raob. The Pasquill category of B (moderately unstable) derives from the fact that it is midafternoon, so surface heating is peaking. Also, light surface winds allow the surface heating to continue unimpeded. From the ballistic met message, one can determine range error. As an example, for the ballistic met plot for 21Z, 12 Dec (figure 2b), at zone 3 (top = 1 km) VEM differs from the raob value by about 0.9 percent, while NGR differs from the raob by about 0.4 percent. This translates to range errors of 0.9* 22 = 19.8 m and 0.4 * 22 = 8.8 m, respectively, for VEM and NGR.

To be consistent in this study, the previous day's max and min temperatures were used for input. This case is in the afternoon so the minimum temperature for the day will already have occurred if this is a typical day. By using today's minimum temperature and yesterday's maximum (unless today's current temperature already exceeds yesterday's max) temperature a more accurate profile could be derived.



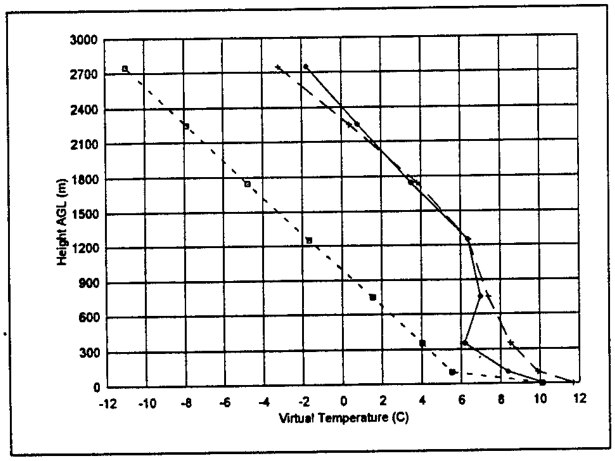
(a) **(b)**

Figure 3. (a) VEM, NGR, and raob virtual temperature; and (b) 100 + % departure from standard atmosphere temperature plots for 13 Dec 96, 19Z. raob = <>; NGR = +; VEM = square.

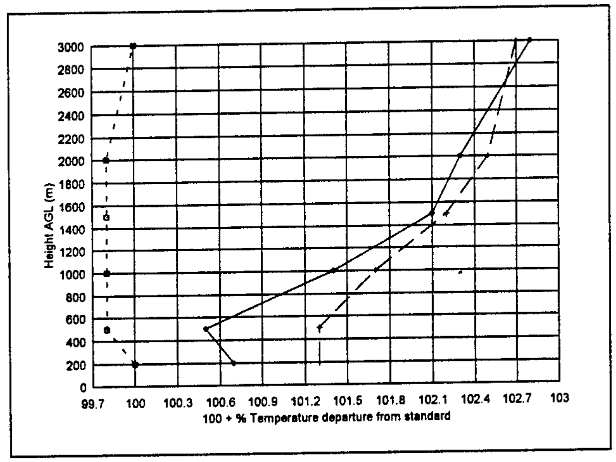
13 Dec 96

1834 GMT
Yesterday's max/min temperature: 20.6/1.7 °C
Today's max/min temperature: 21.7/-1.7 °C
Surface wind speed: 2.7 kn
Cloud cover: 0
Ceiling height: not applicable
Pasquill category: A

On 13 Dec (figure 3a), Tmean is too low again; however, the built-in bias is much too small to compensate for the poor Tmean estimation. The lack of a previous raob does not allow for a bias adjustment. Category A (highly unstable) results since it is the time of maximum heating and again winds are light. Above 1200 m VEM is almost 6 °C too cool. The NGR and raob profiles nearly coincide above 1200 m.



(a)



(b)

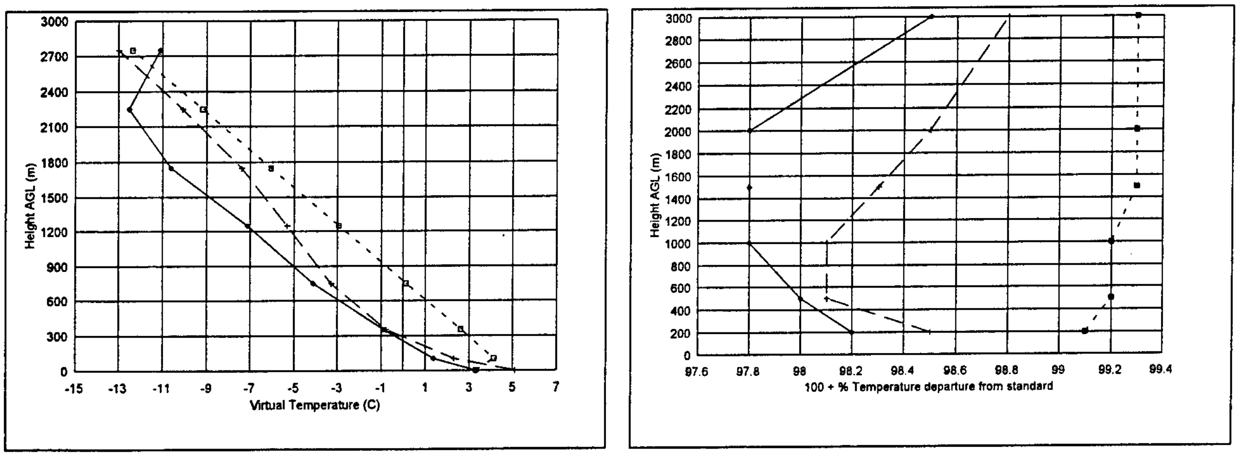
Figure 4. (a) VEM, NGR, and raob virtual temperature; and (b) 100 + % departure from standard atmosphere temperature plots for 16 Dec 96, 22Z. raob = <>; NGR = +; VEM = square.

16 Dec 96

2202 GMT

Yesterday's max/min temperature: 10.6/-2.2 °C
Today's max/min temperature: 12.8/-7.2 °C
Surface wind speed: 2.9 kn
Cloud cover: 0
Ceiling height: not applicable
Pasquill category: B

Figure 4a, 16 Dec, is a similar situation in which the built-in bias is too small and VEM underestimates even more, on the order of 5 °C. The regression coefficients tuned for the southern end of WSMR cause NGR to underestimate below 750 m, but provide for quite good accuracy above that height. As in the preceding two days, the Pasquill category is unstable, given the fact that it is late afternoon, moderate solar heating is still occurring and winds remain light.



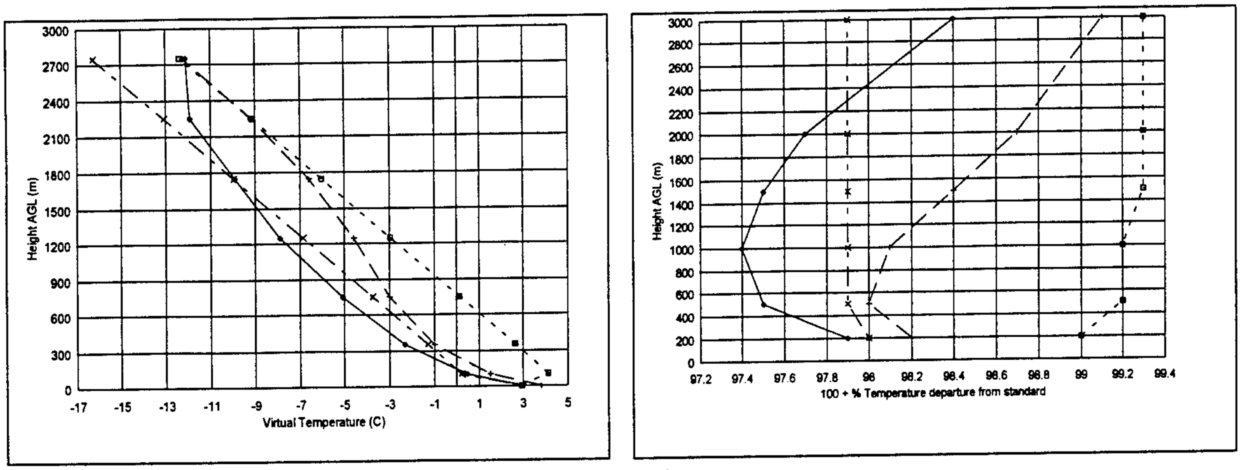
(a) (b)

Figure 5. (a) VEM, NGR, and raob virtual temperature; and (b) 100 + % departure from standard atmosphere temperature plots for 17 Dec 96, 2118Z. raob = <>; NGR = +; VEM = square.

17 Dec 96

2118 GMT
Yesterday's max/min temperature: 12.8/-7.2 °C
Today's max/min temperature: 4.4/-6.7 °C
Surface wind speed: 8.16 kn
Cloud Cover: 0
Ceiling height: not applicable
Pasquill category: C

In the virtual temperature plot of figure 5a, 17 Dec, 21Z, there is an upper level inversion (above 2250 m) and neither the VEM nor NGR capture it. The VEM can model surface inversions based on the Pasquill categories; however, higher inversions cannot be modeled since VEM uses an adjustment to the standard atmosphere profile and this adjustment becomes quite small above a few hundred meters. At 2118 GMT, the relatively strong surface wind has mitigated the surface heating somewhat producing Pasquill category C (slightly unstable). Strong winds have the effect of creating a more well-mixed atmosphere and thus increasing stability. The large error in the VEM computer met plot is mirrored in the VEM ballistic met plot.



(a) **(b)**

Figure 6. (a) VEM, NGR, and raob virtual temperature; and (b) 100 + % departure from standard atmosphere temperature plots for 17 Dec 96, 2224Z. raob = <>; NGR = +; VEM = square; VMP = X.

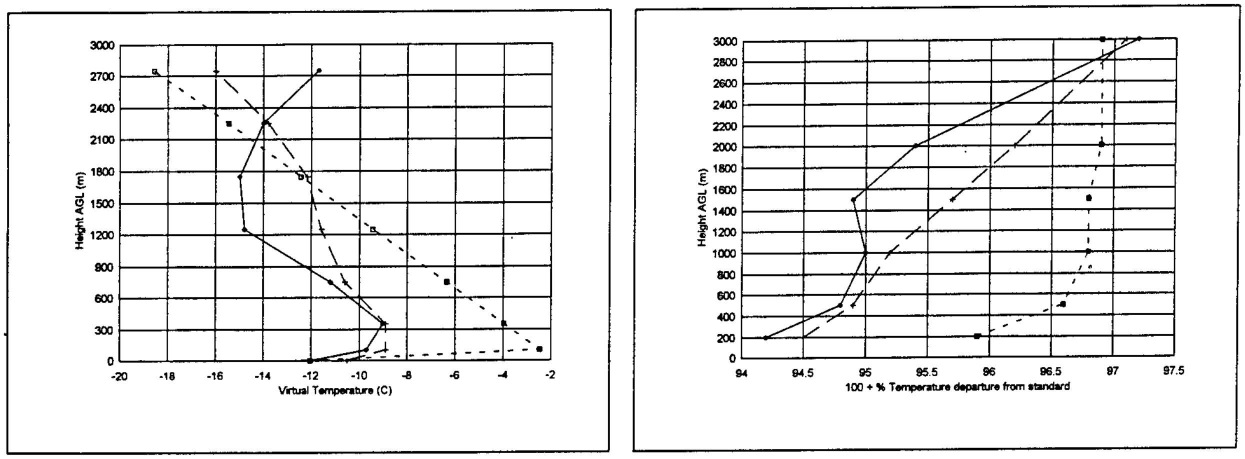
17 Dec 96

2224 GMT

Yesterday's max/min temperature: 12.8/-7.2 °C
Today's max/min temperature: 4.4/-6.7 °C
Surface wind speed: 7.8 kn
Cloud Cover: 0
Ceiling height: not applicable
Pasquill category: B

On 17 Dec, 2224 GMT represents the first time a bias correction could be applied. Note the dramatic improvement VMP provides over VEM. The bias adjustment has also improved the accuracy of the ballistic met temperature plot (figure 6b) for VEM. By 2224 GMT, a very slight easing of the winds has allowed the surface layer to destabilize slightly to category B (moderately unstable). The nearly isothermal layer between 2250 and 2750 m is captured neither by VEM nor NGR. VEM will not be able to model this for the same reason it cannot model high-level inversions.

For this afternoon case, the minimum temperature for the day is already known. Furthermore, it should be readily apparent that given the 2224 GMT temperature of about 3 °C, the previous day's high of 12.8 will not be attained. Given that it is wintertime, solar warming has nearly peaked. Therefore, a better VEM profile would have been attained if today's minimum were used along with the current temperature for the maximum.



(a) (b)

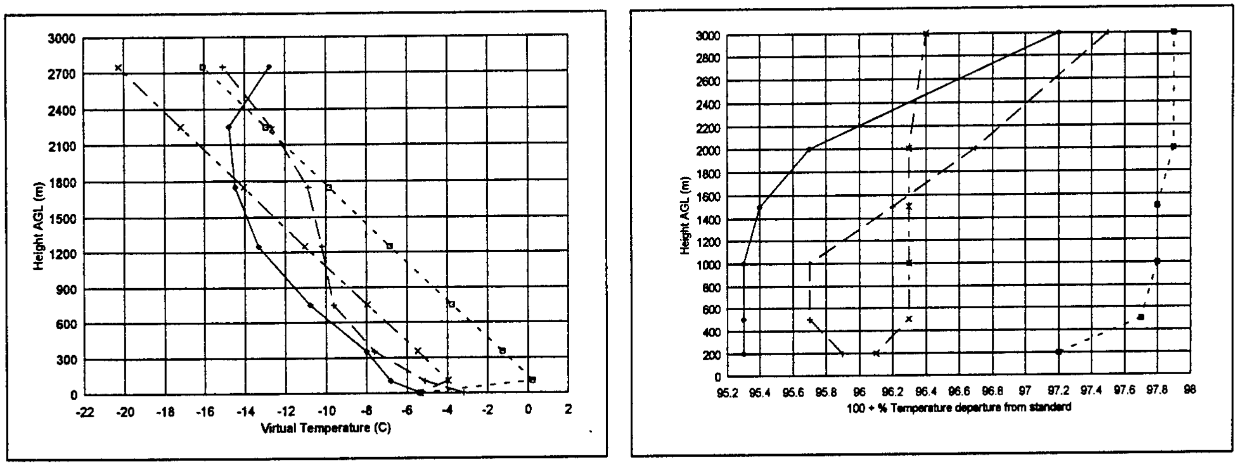
Figure 7. (a) VEM, NGR, and raob virtual temperature; and (b) 100 + % departure from standard atmosphere temperature plots for 18 Dec 96, 1423Z. raob = <>; NGR = +; VEM = square.

18 Dec 96

1423 GMT

Yesterday's max/min temperature: 4.4/-6.7 °C
Today's max/min temperature: 2.8/-14.4 °C
Surface wind speed: 2.9 kn
Cloud cover: 0
Ceiling height: not applicable
Pasquill category: C

On 18 Dec at 14Z, the actual min and max temperatures are -14 °C and 3 °C, respectively, while the values used for VEM are -7 °C and 4 °C, the min and max temperatures for 17 Dec. This has the effect of making Tmean much too large and shifting the virtual temperature profile too far to the right. Given a relatively small solar altitude, no cloud cover, and a wind speed of 1.5 m/s the stability module within VEM derives a Pasquill category of C, which is slightly unstable. This is an extreme temperature case in that we have a surface and an upper level inversion. The Pasquill categorization here is wrong. Due to a current deficiency in the Pasquill categorization software module, obtaining a stable classification outside of nighttime hours is impossible.



(a) **(b)**

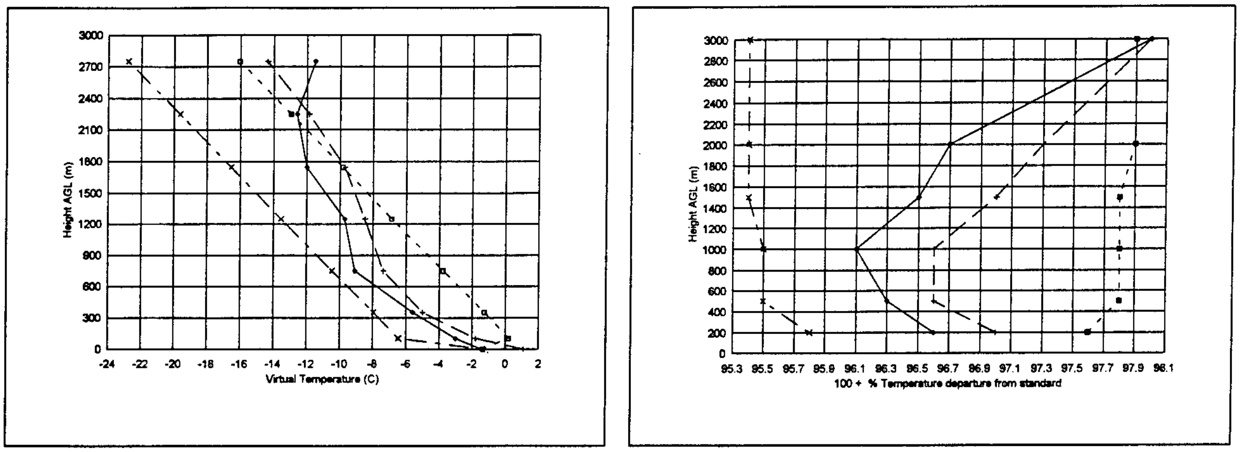
Figure 8. (a) VEM, NGR, and raob virtual temperature; and (b) 100 + % departure from standard atmosphere temperature plots for 18 Dec 96, 1714Z. raob = <>; NGR = +; VEM = square; VMP = X.

18 Dec 96

1714 GMT

Yesterday's max/min temperature: 4.4/-6.7 °C
Today's max/min temperature: 2.8/-14.4 °C
Surface wind speed: 1.9 kn
Cloud cover: 0
Ceiling height: not applicable
Pasquill category: A

At 17Z, the Pasquill categorization is correct; yet, the VEM indicates a surface inversion which is nonexistent. This stems from the fact that Tmean + the built-in bias + the bias adjustment is too large, which resulted in that above 100 m, the VEM profile is over 4 °C too warm. However, the bias adjustment has made the VMP profile significantly more accurate.



(a) **(b)**

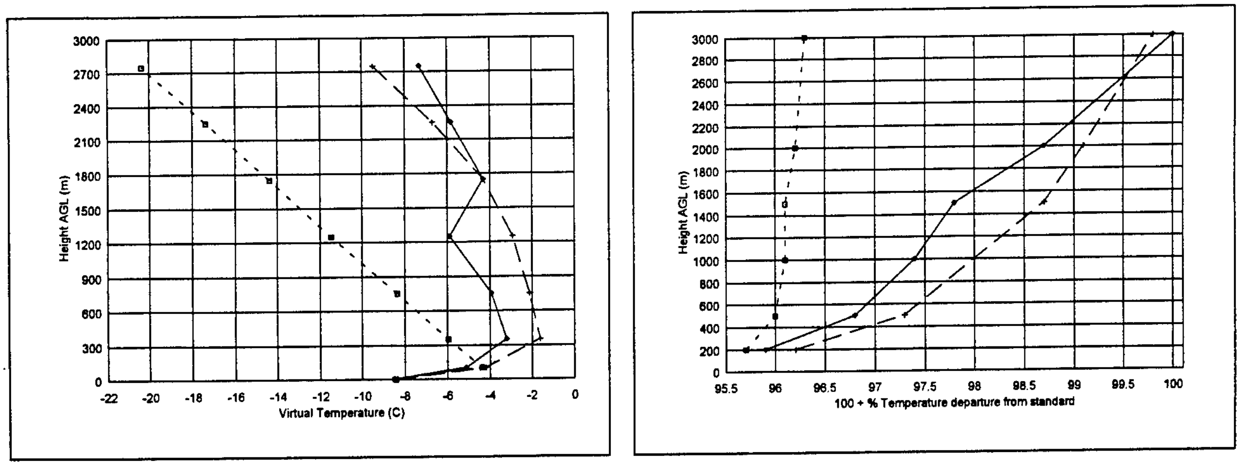
Figure 9. (a) VEM, NGR, and raob virtual temperature; and (b) 100 + % departure from standard atmosphere temperature plots for 18 Dec 96, 2003Z. raob = <>; NGR = +; VEM = square; VMP = X.

18 Dec 96

2003 GMT

Yesterday's max/min temperature: 4.4/-6.7 °C
Today's max/min temperature: 2.8/-14.4 °C
Surface wind speed = 1.0 kn
Cloud cover: 0
Ceiling height: not applicable
Pasquill category: A

At 20Z, figure 9a, a bias adjustment has been applied to the VEM profile. Again, VEM produces a false inversion for the same reason as at 17Z.



(a) **(b)**

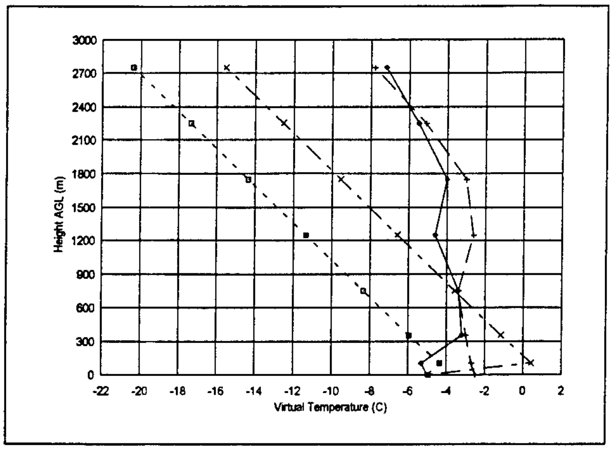
Figure 10. (a) VEM, NGR, and raob virtual temperature; and (b) 100 + % departure from standard atmosphere temperature plots for 19 Dec 96, 1405Z. raob = <>; NGR = +; VEM = square.

19 Dec 96

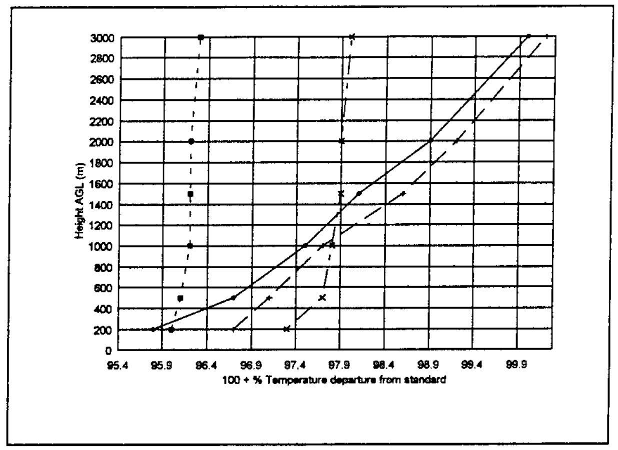
1405 GMT

Yesterday's max/min temperature: 2.8/-14.4 °C
Today's max/min temperature: 8.3/-11.7 °C
Wind speed = 2.9 kn
Cloud cover: 0
Ceiling height: not applicable
Pasquill category: C

The VEM poor estimate for 1405 GMT on 19 Dec stems from the fact that the actual min and max temperatures for that day are -11.7 °C and 8.3 °C respectively. The min and max temperatures used as input to VEM were -14.4 °C and 2.8 °C, respectively, which are the min and max values for 18 Dec 96. This causes Tmean (the average of the min and max temperatures) to be too small. If Tmean is too small, the temperature profile is shifted to the left of where it should be. Because this is the first raob launch of the day, no bias adjustment can be used and the built-in bias turns out to be too small. Figure 10a shows that the VEM virtual temperature profile is approximately 5 °C too cool at 350 m increasing to 13 °C too cool at 2750 m. This error is correctly reflected in the ballistic met temperature profile (figure 10b) for the VEM as well. Again, the Pasquill categorization is wrong for the same reason as cited earlier. The appropriate category would be either E or F, indicating a stable lower atmosphere.



(a)



(b)

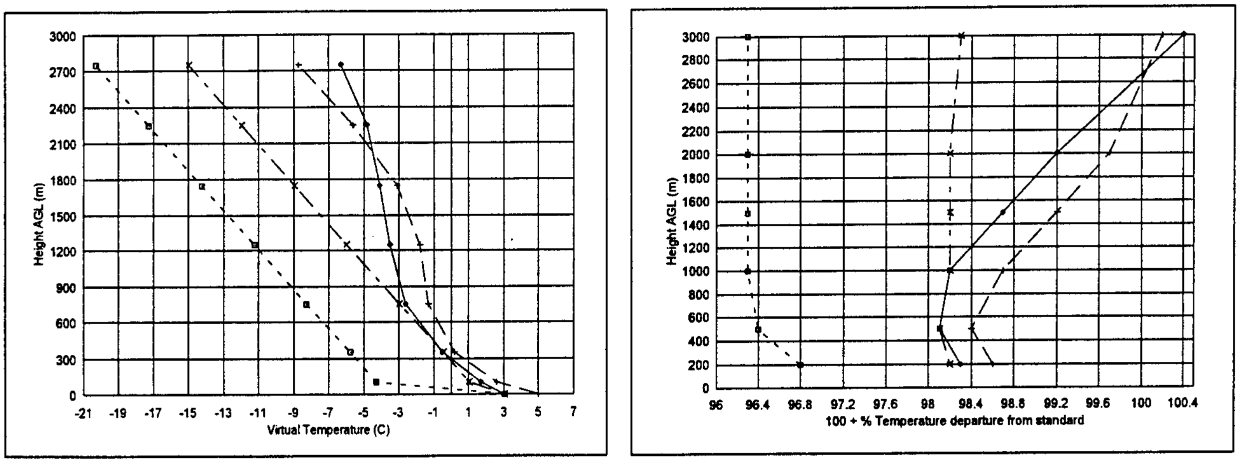
Figure 11. (a) VEM, NGR, and raob virtual temperature; and (b) 100 + % departure from standard atmosphere temperature plots for 19 Dec 96, 1646Z. raob = <>; NGR = +; VEM = square; VMP = X.

19 Dec 96

1646 GMT
Yesterday's max/min temperature: 2.8/-14.4 °C
Today's max/min temperature: 8.3/-11.7 °C
Wind speed = 1.9 kn
Cloud cover: 0
Ceiling height: not applicable
Pasquill category: B

By 1646Z, figure 11a, the VEM profile is about 10 °C too cool at 1750 m and 13 °C too cool at the top of the profile. The bias adjustment provides a VMP profile, which is significantly better. The bias adjustment in this case was positive, which effectively translates the entire profile to the right.

A problem that the VEM has that is evidenced here, is that it will always more closely parallel a standard atmosphere profile with height, and the raob profile in this case is far from standard. One way to partially remedy this deficiency is to give the capability to the VEM to add a bias adjustment at every height, not just 750 m. So if there has been a previous raob, a more representative profile can be obtained from the current surface data.



(a) **(b)**

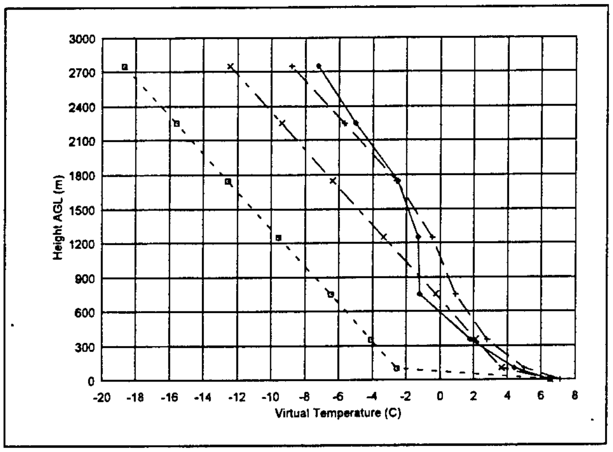
Figure 12. (a) VEM, NGR, and raob virtual temperature; and (b) 100 + % departure from standard atmosphere temperature plots for 19 Dec 96, 1950Z. raob = <>; NGR = +; VEM = square; VMP = X.

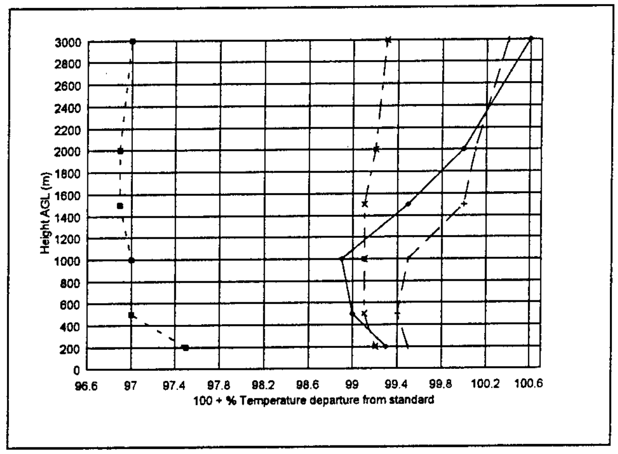
19 Dec 96

1950 GMT

Yesterday's max/min temperature: 2.8/-14.4 °C
Today's max/min temperature: 8.3/-11.7 °C
Wind speed = 2.9 kn
Cloud cover: 0
Ceiling height: not applicable
Pasquill category: A

At 1950Z, the bias adjustment has done an excellent job in matching up the VMP profile with the raob, at least up to 750 m. Because the VMP parallels the standard atmosphere slope more and more with height, it deviates from the raob profile, which is not that of a standard atmosphere.





(a) **(b)**

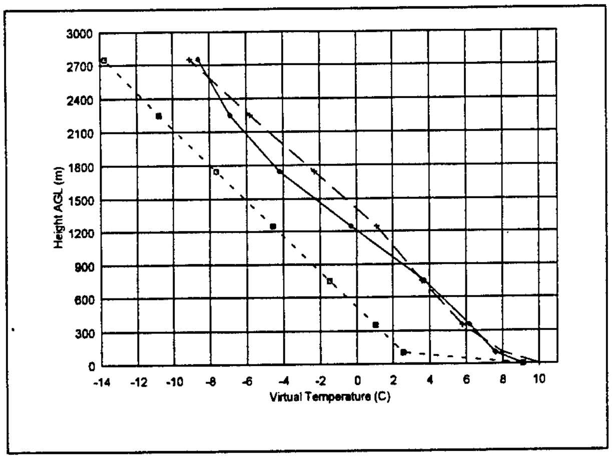
Figure 13. (a) VEM, NGR, and raob virtual temperature; and (b) 100 + % departure from standard atmosphere temperature plots for 19 Dec 96, 2154Z. raob = <>; NGR = +; VEM = square; VMP = X.

19 Dec 96

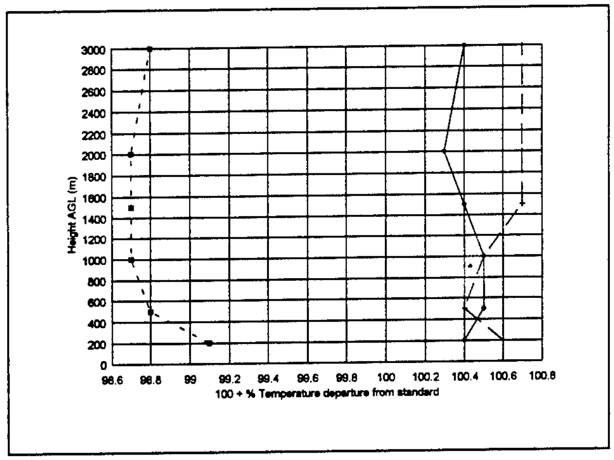
2154 GMT

Yesterday's max/min temperature: 2.8/-14.4 °C
Today's max/min temperature: 8.3/-11.7 °C
Wind speed = 1.9 kn
Cloud cover: 0
Ceiling height: not applicable
Pasquill category: A

By 2154Z (figure 13a), VMP and NGR have roughly the same accuracy below 1250 m and the NGR profile is much better above that point because it is not restricted to a standard atmosphere slope. Note how much better VMP is than VEM. With light winds and solar heating, the Pasquill category correctly becomes more unstable with time.



(a)



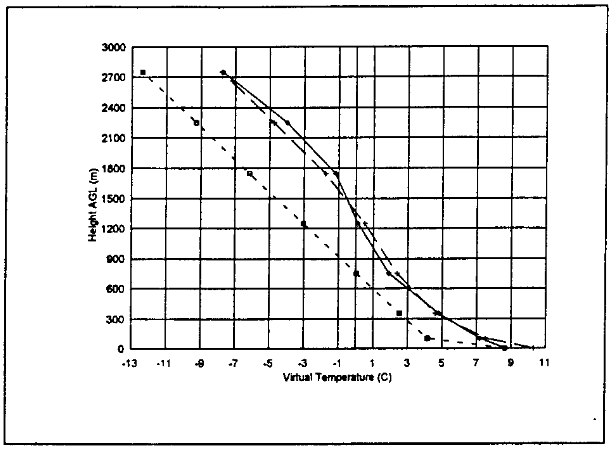
(b)

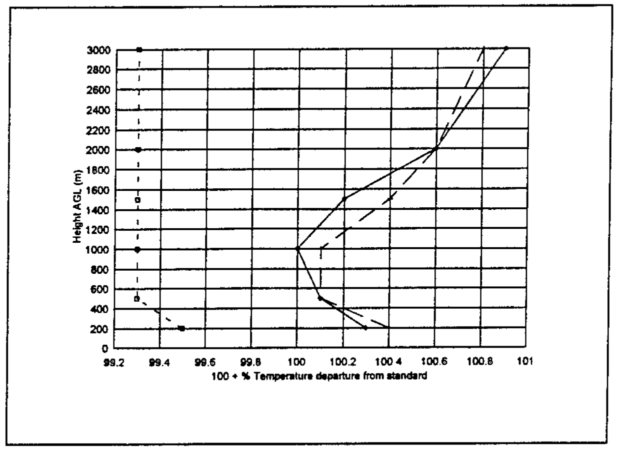
Figure 14. (a) VEM, NGR, and raob virtual temperature; and (b) 100 + % departure from standard atmosphere temperature plots for 14 Jan 97, 21Z. raob = <>; NGR = +; VEM = square.

14 Jan 97

2127 GMT

Yesterday's max/min temperature: 1.7/-6.7 °C
Today's max/min temperature: 11.1/-5.6 °C
Surface wind speed: 9.9 kn
Cloud cover: 0
Ceiling height: not applicable
Pasquill category: B





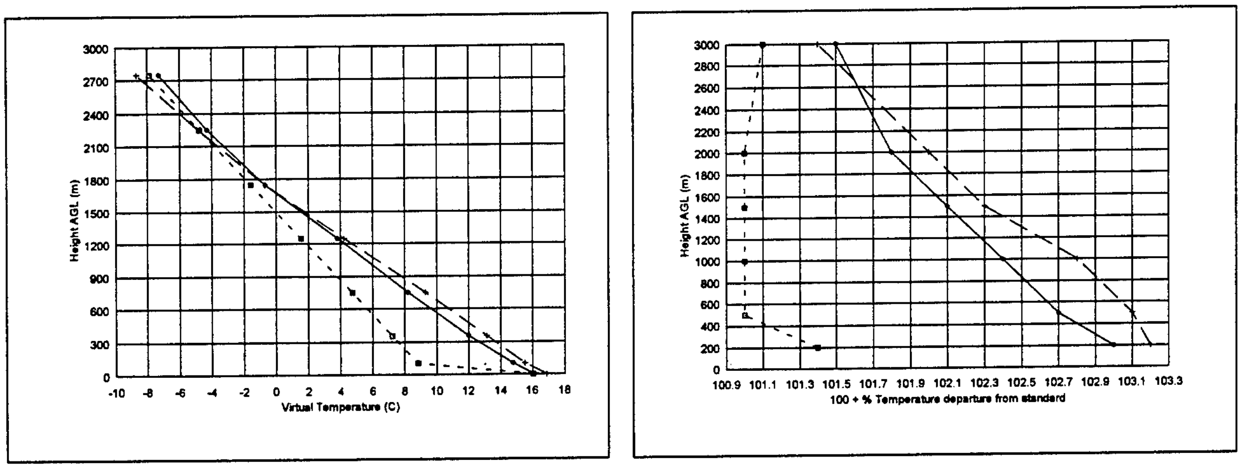
(a) **(b)**

Figure 15. (a) VEM, NGR, and raob virtual temperature; and (b) 100 + % departure from standard atmosphere temperature plots for 15 Jan 97, 22Z. raob = <>; NGR = +; VEM = square.

15 Jan 97

2138 GMT

Yesterday's max/min temperature: 11.1/-5.6 °C
Today's max/min temperature: 10.6/-3.9 °C
Surface wind speed: 10.7 kn
Cloud cover: 0
Ceiling height: not applicable
Pasquill category: C



(a) **(b)**

Figure 16. (a) VEM, NGR, and raob virtual temperature; and (b) 100 + % departure from standard atmosphere temperature plots for 23 Jan 97, 22Z. raob = <>; NGR = +; VEM = square.

23 Jan 97

2135 GMT
Yesterday's max/min temperature: 16.1/-1.1 °C
Today's max/min temperature: 17.8/6.7 °C
Surface wind speed: 7.77 kn
Cloud cover: 0
Ceiling height: not applicable
Pasquill category: B

For three days in January, illustrated in figures 14 to 16, NGR generally outperforms VEM as illustrated in the ballistic met temperature plots; although on 23 Jan (figure 16a), the three profiles nearly coincide above 1750 m. What would otherwise be a highly unstable category on 15 Jan is made slightly more stable by the strong surface winds.

4.3 Temperature Impact Displacements

As described in section 3.2, the ballistic temperature and firing table (FT 155-AO-O) unit effects can be used to estimate the expected target impact displacement. For this study, the effects on a rocket-assisted round are derived for the following three ranges: 15, 20, and 22 km with corresponding apogees at 1, 2, and 3 km.

Figures 17 to 19 illustrate the impact miss distance, taking only virtual temperature into account, for each time period over three different ranges. When there is either one sounding for the day, or it is the first sounding of the day, there is no error bar for VMP, as VMP requires a prior sounding to be run. Note that the NGR estimate causes misses of at most 30 m for all target ranges.

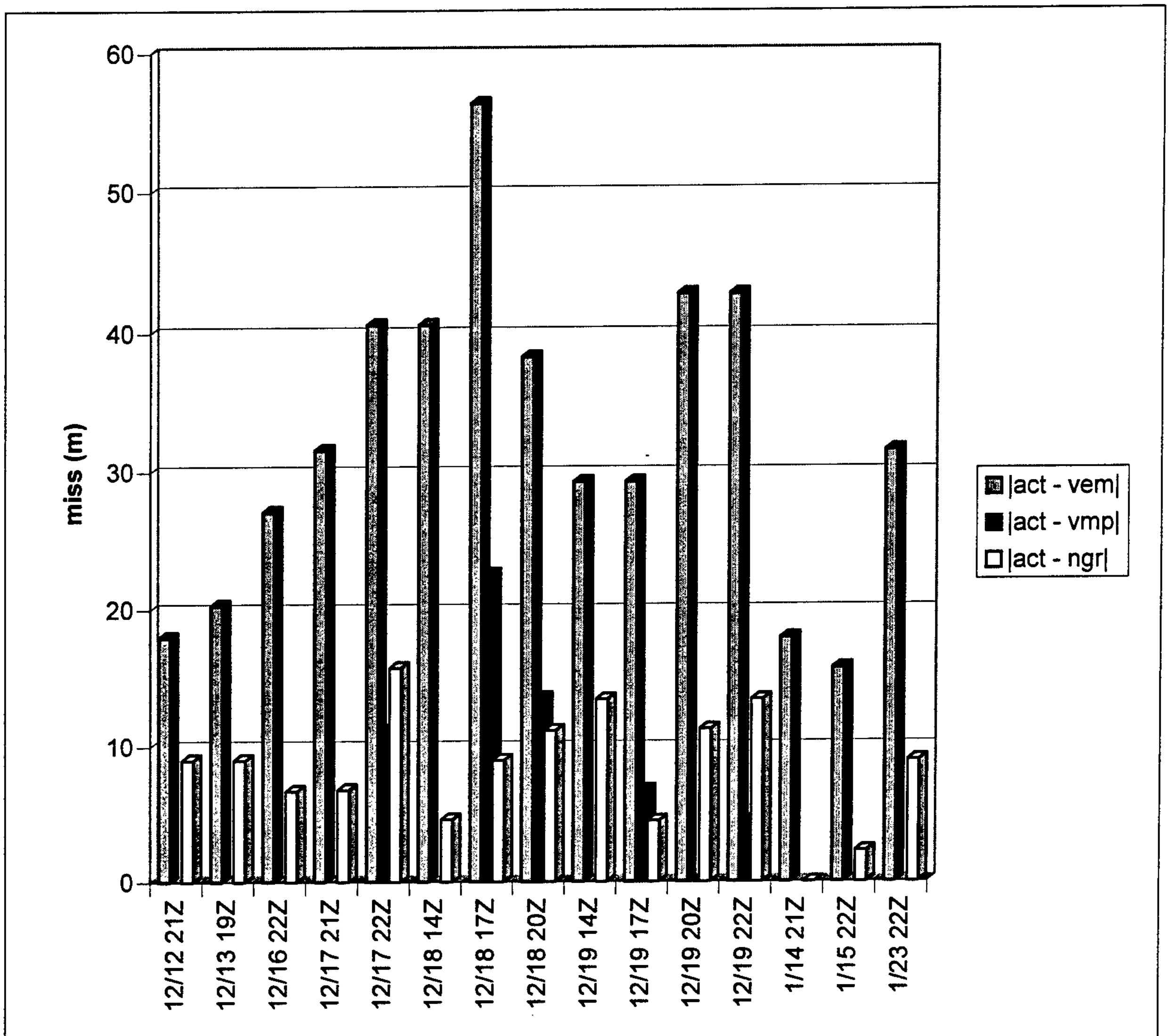


Figure 17. Virtual temperature component of target error at a 15-km range (Dec 96 - Jan 97).

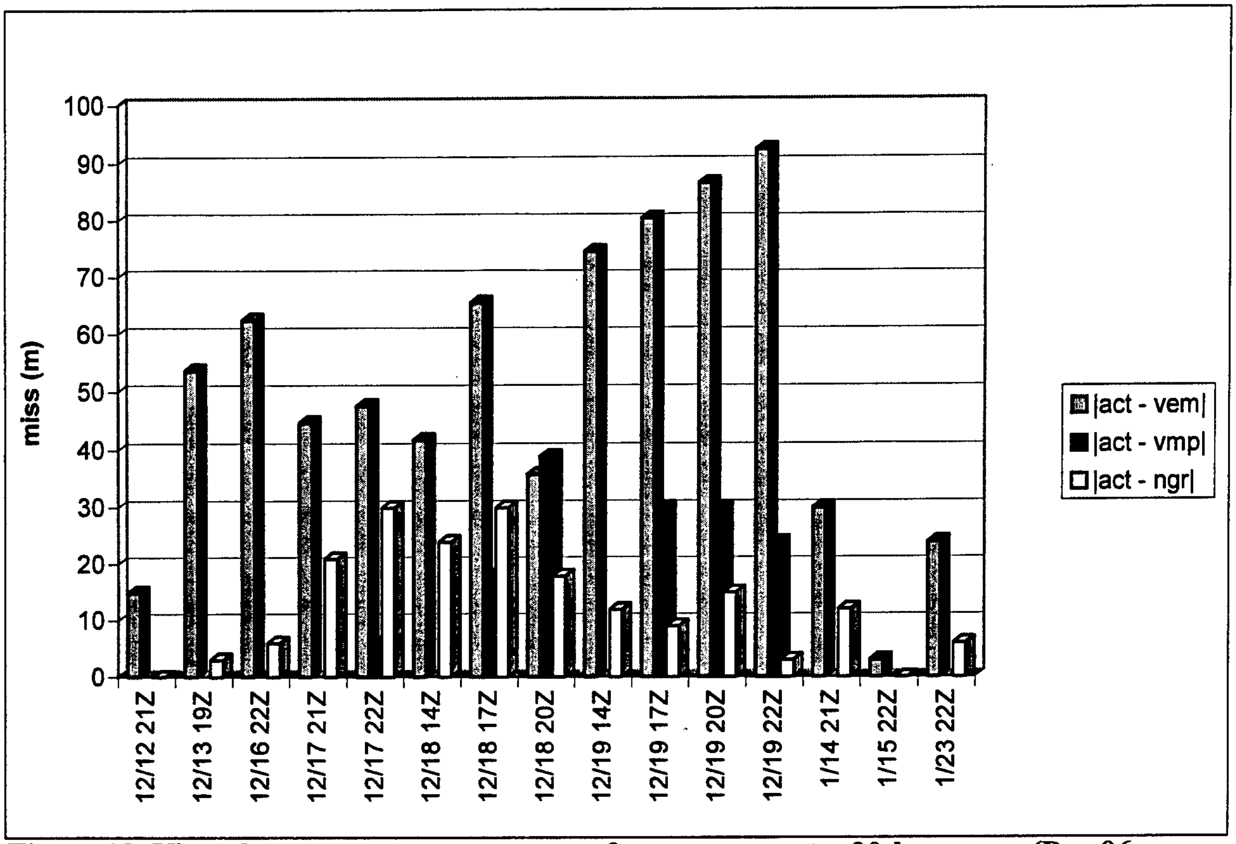


Figure 18. Virtual temperature component of target error at a 20-km range (Dec 96 - Jan 97).

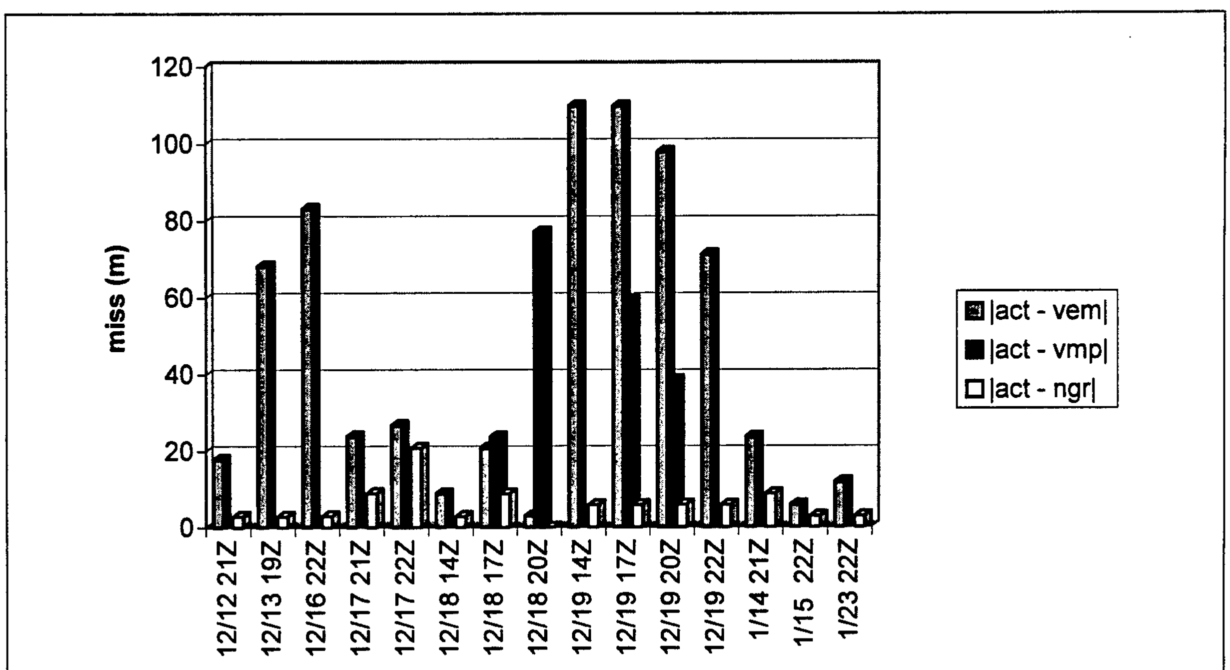


Figure 19. Virtual temperature component of target error at a 22-km range (Dec 96 - Jan 97).

Assuming a lethal radius of 50 m for a round delivered by a 155-mm howitzer, one can see from figure 17 that VEM/VMP temperatures always allow the projectile to land within this radius shooting at a 15-km range. (Note: when there is only one balloon flight in a day, or it is the first flight of the day, the VEM estimate is used; otherwise, the VMP estimate is used.) At a 20-km range (figure 18), there are three time periods (13 Dec at 19Z, 16 Dec at 22Z, and 19 Dec at 14Z) when the VEM/VMP output temperature data used for the projectile firing causes a target miss of greater than 50 m. Figure 19 (22-km range) illustrates that a projectile using VEM/VMP temperature data for aiming is outside the lethal radius 5 times out of 15 (at 12/13 19Z, 12/16 22Z, 12/18 20Z, 12/19 14Z, and 12/19 17Z). On 18 Dec at 20Z, it turns out that VMP produces results much worse than the VEM. This is because the bias adjustment is too large in the negative direction as described in section 3.2.

Another approach is to examine the average miss. Over the 15 time periods the target miss rmses for VEM/VMP due to virtual temperature effects only were:

- 15-km range - 29.1 m (VEM/VMP 19.5 m farther off target (on average) than NGR),
- 20-km range - 39.8 m (VEM/VMP 23.6 m farther off target than NGR), and
- 22-km range - 51.4 m (VEM/VMP 43.6 m farther off target than NGR).

4.4 Temperature/Density Impact Displacements

The target miss error due to density was also examined using virtual temperature. The VEM/VMP mean target miss errors (due to density only) were:

- 15-km range - 67.5 m (VEM/VMP 36.2 m farther off target than NGR),
- 20-km range - 124.4 m (VEM/VMP 66 m farther off target than NGR), and
- 22-km range - 160.6 m (VEM/VMP 121.7 m farther off target than NGR).

The average of the virtual temperature effect rmse and density (using virtual temperature) effect rmse for VEM/VMP was 48.3 m at a 15-km range, 82 m at a 20-km range, and 106 m at a 22-km range. The average of the virtual temperature and density (using virtual temperature) effect rmse for NGR is 20.5 m at a 15-km range, 37.3 m at a 20-km range, and 23.4 m at a 22-km range.

The NGR clearly provides significantly better estimates of temperature and density than the VEM. Note that the temperature provides the smallest contribution to the artillery error budget.

Based on the expected accuracy of firing an M549A1 rocket-assisted round at a 25-km range target using 2-h old and 20-km displaced met, Reichelderfer reports a total range bias error of 202 m (standard deviation). She lists the following met error contributions: 10 m for temperature, 50 m for density, and 122 m for wind. The temperature and density errors affect the range, but not the deflection. [5]

4.5 Persistent Temperature/Density Effects

Note that when VEM, VMP, or NGR temperatures are used, the temperature error components for the 22-km range are, on average, much larger than the Reichelderfer value of 10 m for the 25-km range error. If one uses persistence, that is, use a 2-h old radiosonde measurement launched 20 km away, then the expected temperature component of target miss for a 25-km range shot will be 10 m based on the Reichelderfer study. [5] Is persistence of 2-h old data a better estimator than VEM, VMP, and NGR? Our data sample contains three days, 17 to 19 Dec 96, on which there were multiple radiosonde launches. Comparisons were made between a radiosonde at time t0 and another radiosonde at time t1 (1 to 3 h later). This small sample indicates how well persistence does in comparison to VEM and NGR. For 17 Dec, we examined 1-h old data compared to the actual and to VEM and NGR. For 18 Dec, there are raobs at 14Z, 17Z, and 20Z, which provide two cases of 3-h old data. For 19 Dec, raob launches were taken at 14Z, 17Z, 20Z, and 22Z, yielding two cases of 3-h old data and one case of 2-h old data. The persistence error was taken to be the rms of raob temperature at time t0 - raob temperature at time t1 for eight height levels. The VEM error is the rms of VEM temperature at time t1 - raob temperature at time t1 for ballistic line 6 (3 km above the surface). The results are shown in tables 2 and 3.

Table 2. The rms errors for six cases in Dec 96 showing the miss on a 22-km range target using 1- to 3-h old persistence data

	raob (%)	delta (%)	rms (%)	miss(m)
1 h: 17 Dec 21Z	98.50			
17 Dec 22Z	98.40	0.10	0.10	3.00
2 h: 19 Dec 20Z	100.40			
19 Dec 22Z	100.60	0.20	0.20	6.00
3 h: 18 Dec 14Z	97.20			
18 Dec 17Z	97.20	0.00		
18 Dec 20Z	98.00	0.80		
3 h: 19 Dec 14Z	100.00			
19 Dec 17Z	100.00	0.00		
19 Dec 20Z	100.40	0.40	0.50	15.00

Table 3. Persistence method compared to model (VEM/VMP) and measurement (NGR) methods

	Raob	Per	NGR	VEM	VMP
17 Dec 22Z	98.40	98.50	99.10	99.30	97.90
abs Delta (%)		0.10	0.70	0.90	0.50
miss (m)		3.00	21.00	27.00	15.00
19 Dec 22Z	100.60	100.40	100.40	97.00	99.30
abs Delta (%)		0.20	0.20	3.60	1.30
miss (m)		6.00	6.00	108.00	39.00
18 Dec 17Z	97.20	97.20	97.50	97.90	96.40
abs Delta (%)		0.00	0.30	0.70	0.80
miss (m)		0.00	9.00	21.00	24.00
18 Dec 20Z	98.00	97.20	98.00	97.90	95.40
abs Delta (%)		0.80	0.00	0.10	2.60
miss (m)		24.00	0.00	3.00	78.00
19 Dec 17Z	100.00	100.00	100.20	96.30	98.00
abs Delta (%)		0.00	0.20	3.70	2.00
miss (m)		0.00	6.00	111.00	60.00
19 Dec 20Z	100.40	100.00	100.20	96.30	98.30
abs Delta (%)		0.40	0.20	4.10	2.10
miss (m)		12.00	6.00	123.00	63.00

The smallest persistence error occurred when the raobs were only 1 h apart, which is logical, because more recent data will be more representative of current conditions. Table 2 lists the three time stalenesses with the 3-h containing multiple replicates. The 6-m miss derived from the one replicate for the 2-h old persistent data is a good estimator of the Reichelderfer result of 10 m. [5] One can expect the 6 m to approach the 10 m when one uses a 2-h old measurement from a radiosonde launched 20 km away.

Table 3 lists the comparison results for the six cases. For the 1-h stale data, persistence provided the best estimate. For the 2-h stale data, persistence and NGR provided the best estimates, while the VEM/VMP results caused misses that were too large (see section 3.2). The four replicate 3-h stale results in table 3 are composed into an rms value. The results are summarized as follows: persistence = 15 m; NGR = 7 m; VEM = 90 m; and VMP = 61 m.

5. Conclusions

Considering the rmse for VEM/VMP and NGR virtual temperatures in comparison to raob virtual temperature (converted from sensible) over 15 time periods, it is apparent that NGR can more accurately estimate vertical virtual temperature profiles by about 3.5 °C. This is the error when all nine zones (surface to 4 km) are considered.

When the effects of virtual or sensible temperature only are considered, NGR output data allowed the projectile to land closer to the target. In reference to the mean miss, the VEM/VMP output data always put the mean impact point within the lethal radius of 50 m at all three ranges (15, 20, and 22 km). Note that in all these results, when VMP data was available it is used instead of the VEM data because it is generally better.

For the case of the effects on the projectile due to density, NGR output data always allowed the projectile to land closer to the target.

When the rms miss errors for virtual temperature and density effects on the projectile are averaged, NGR output data allowed the projectile to land within the lethal radius of 50 m at all three ranges: 15, 20, and 22 km. At a 15-km range, VEM/VMP output data, on the average, allowed the projectile to land within the lethal radius of 50 m when virtual temperature and density effects are considered in combination.

These numbers show that although the NGR was generally more accurate in temperature and density profile estimation, the VEM is an effective estimator for shorter range targets and is a simple software package that does not require any tuning for a particular climatic regime. Furthermore, although the VEM is designed as a backup to the MMS, it is the major software providing met adjustments to the light forces that move in on the first days of a conflict. On these first days, no long range fires over 15 km are expected. The operation is focused on taking control and only engaging short range (3 to 12 km) targets. The artillery batteries are mostly firing direct fire missions. Under these conditions, results have been shown indicating that the VEM (installed in the SMS) can provide a significant improvement over that of using standard met conditions. [1]

6. Recommendations

There are ways to improve the estimates for min and max temperatures and thus the Tmean value used in VEM. For the cases in this study, the min and max temperatures for the previous day were used. When the met conditions are quiescent, this is a valid practice. However, for 17 Dec, conditions changed rapidly. The high for 16 Dec exceeds the high for 17 Dec by 9 °C. If one were running the VEM early in the day, it would be difficult to foresee this problem; however, if it were run at around noon it should be quite evident to the operator that the high will not reach the preceding day's and should be adjusted accordingly. For the case of 18 Dec, the previous day's min grossly under predicts the actual min. If the VEM were used at 2 a.m., it would be too early to predict a min, although the trend should indicate it needs to be decreased. On the other hand, if it were run at sometime after 7 a.m., the min would likely be known and only the max would have to be estimated. If the input min and max temperatures are good estimates of what the actual ones will be, then problems like false inversions can be avoided. Thus, the operator must strive to make good estimates of the input min and max temperatures. However, if these estimates are poor, the error can be "corrected" on a subsequent run by introducing a bias adjustment to translate the temperature profile.

The Pasquill categorization module performed fairly well, failing to assess the lower atmosphere stability twice. For these particular cases, it is early morning, skies are clear, and a strong surface inversion exists. Yet the Pasquill categorization code produced category C, slightly unstable. With the Pasquill code in its current state, a category E or F (stable) can only be obtained when the sun is below the horizon. In particular, in the Pasquill module, if it is nighttime and total cloud cover <= 40%, then a net radiation index of -2 results. If the total cloud cover is > 40%, then the net radiation is set to -1. The net radiation serves as the column index for a table of Pasquill stability categories. Then assuming winds (which serve as the row index for the table) are very light, a category E or F can occur. The code needs to be modified so a stable category is possible in the very early morning with clear skies and light winds. Strong surface inversions occur under these conditions and the Pasquill categorization code should produce a stable category accordingly.

We believe that although the VMP method performed better than VEM, it can be improved further by taking the temperature differences between the prior raob and VEM run at every height level providing a bias adjustment for every height. Currently, only the 750-m level is used. This should provide a more accurate VMP profile because differences at the 750-m level are not necessarily representative of the atmosphere above and below that height.

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Acronyms and Abbreviations

AGL	above ground level
ARL	U. S. Army Research Laboratory
IF	intermediate frequency
LTE	local thermodynamic equilibrium
met	meteorological
MMS	Meteorological Measuring Set
MMS-P	Meteorological Measuring Set - Profiler Prototype
NGR	Next Generation Radiometer
raob	radiosonde observation
rms	root mean square
rmse	root mean square error
SMS	Semiautomatic Meteorological Station
VEM	Vertical Extrapolation Model
VMP	Vertical Extrapolation Model enhanced with a temperature bias and second-level wind information from a prior raob
WSMR	White Sands Missile Range
Z	Zulu Time (equivalent to GMT time)

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