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Meteorological Error Budget Using Open-Source Data

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14. ABSTRACT

The meteorological (MET) error budget tables for artillery list MET errors that are based on radiosonde observations (RAOBs) at various "staleness" increments. Staleness increments are in terms of time (e.g., "30-min MET") or equivalent distance from the RAOB launch site. The values in the tables represent levels of error extracted from extensive sets of RAOB data generated several decades ago. The US Army Armament Research, Development, and Engineering Center asked for assistance to produce artillery MET error budget tables that account for expected errors when using MET model-based systems. Representatives of the US and other nations within the North Atlantic Treaty Organization expressed a need for shareable model-based MET error budgets. Use of an openly available civilian version of a MET model to generate the appropriate values will allow distribution without restrictions that could arise from extracting data from an operational military system. This investigation provides those model-based MET error budget values using an open-source version of the Weather Research and Forecasting (WRF) model. The MET error budget tables are formatted similarly to traditional RAOB-based tables. Consequently, the transition to the model-based tables should not require any significant effort on the part of the user.

15. SUBJECT TERMS

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1. Introduction

The meteorological (MET) error budget for artillery is part of the complete artillery error budget. The MET error budget tables currently list MET errors that are based on data from radiosonde observations (RAOBs) at various increments of "staleness." Staleness is commonly defined in terms of time (e.g., "half-hour or 30-min MET") or equivalent distance from the RAOB (or weather balloon) launch site. The staleness levels denote levels of error extracted from extensive sets of data generated several decades ago. Appendix A presents 3 sample MET error budget sheets. A MET error budget sheet should not be taken as meaning any individual RAOB launched at the specified time in the past (e.g., 1 h ago) will have the exact errors listed in that respective staleness error budget sheet. For example, a balloon launched an hour before a firing or other event may have greater or less error than the 1-h listing depending on weather conditions, terrain, and so on. Furthermore the error values in the existing tables may not accurately reflect the errors likely to occur when using data from a numerical weather prediction (NWP) model-based system

The US Army Research, Development, and Engineering Center (ARDEC), Firing Tables and Ballistics Division asked for assistance to bring their artillery MET error budget tables up to date to account for expected errors when NWP model-based systems such as the Profiler Virtual Module (PVM) are used rather than radiosondes. The current artillery error budget tables are based on the expected errors in the MET parameters as a function of time or equivalent distance from when artillery MET messages are produced using RAOBs. The PVM uses a version of the Weather Research and Forecasting (WRF) model, which includes pre- and postprocessing software. Skamarock et al. (2008) provides information on the basics of the WRF model in some detail. While certain parts have changed and new features added since their paper, the main aspects of the WRF have remained much the same. More recent documentation and other information may be found on the WRF website (http://wrf-model.org/index.php). Additionally, representatives of various member nations within NATO have expressed a need for model-based MET error budget values and US representatives also expressed an interest in having those data shareable within NATO. A freely available civilian version of the WRF model to generate the appropriate values will allow distribution throughout NATO and other partner nations without potential restrictions that could arise from extracting data from an operational military system.

This report presents an analysis and results of the differences between relevant atmospheric variables from computer MET messages (METCMs) and ballistic messages for surface to surface trajectories (METB3s) produced from "soundings" extracted from WRF output and those generated from coincident RAOBs. The differences were first generated for each case or pair of WRF and coincident RAOB METCMs and METB3s by zone for all zones from the surface to the highest zone covered by the RAOB or the WRF output, whichever was lower. The mean, mean absolute error (MAE), standard deviation, and root mean square error (RMSE) of the difference in the atmospheric variables of the 131 METCM and METB3 pairs were computed and entered into tables for each of the message zones. We note that "errors" in the context of this report refer to differences from the coincident RAOBs despite known limitations in accuracy of RAOBs. To help clarify that we are not comparing these data with the exact atmospheric values, from here on, we adopted the terms mean difference (MD), mean absolute difference (MAD), standard deviation of the differences (SD), and root mean square difference (RMSD) instead of mean, MAE, standard deviation, and RMSE, respectively, for use in this report.

This investigation provided model-based MET error budget values using an open-source version of WRF. The tables showing the results are formatted similarly to traditional RAOB-based tables. Consequently, the transition to the model-based tables should not require any significant effort on the part of the user.

2. Procedure

The model-based messages for this study were generated from vertical profiles of MET data derived from WRF output. The vertical profiles (or soundings) were extracted from WRF Network Common Data Form output files via a NCAR Command Language script. WRF, version 3.7.1, was run with 9/3/1-km horizontal grid spacing nested domains. The comparisons for this report used data from the 3-km domain. The initial and boundary conditions for the WRF model were derived from Global Forecast System (GFS) 0.5° horizontal grid spacing with a 3-h time interval. Initialization data were extracted from GFS output found at the National Oceanic and Atmospheric Administration, National Operational Model Archive and Distribution System website (http://nomads.ncdc.noaa.gov/data.php?name=access#hires_weather_datasets). The WRF runs for the analysis of this report did not include the assimilation of observation data such as regional RAOBs. Consequently, the results should provide a conservative set of data that covers nearly the entirety of potential model errors since data assimilation will likely improve model output rather than degrade it. They are also applicable to battlefield systems that may not always have access to observations. Cogan (2016) contains information on the configuration of WRF used here, except that there was no data assimilation and we used the 12-h forecast.

The RAOB-based messages were produced from soundings obtained from the University of Wyoming weather website (http://www.weather.uwyo.edu/upperair/sounding.html). That site contains WMO soundings in several formats including text as used here. As an alternative, if a particular sounding is not available on the primary site, a National Oceanic and Atmospheric Administration website (http://www.esrl.noaa.gov/raobs) archives WMO data in text format.

2.1 Generation of MET Messages

Cogan (2015) describes the methods employed to process the WRF- and RAOB-based profiles into METCM or METB3 messages. Information on the METCM and METB3 formats and structures may be found in FM 3-09.15 (2007), Blaha and Potuzak (2013) as well as in STANAG 4082 (2000) and STANAG 4061 (2000) on the METCM and METB3, respectively. Overall, 131 cases were included for the MET budget computations, where each case consists of a coincident METCM or a METB3 derived from WRF output and from the respective RAOB. Since separate tables were computed for the METCM and the METB3, each type had 131 cases. The differences for each zone for each case comprised one sample. Statistical quantities were computed for all zones from the surface though the topmost zone reached by the RAOB or WRF, whichever was lower. The WRF output extends vertically from the surface or very close to it (e.g., 0 m for pressure, 2 m for temperature, and 10 m for wind) to a little above 20 km above mean sea level (MSL). Consequently, for locations near sea level, the WRF-based profiles will extend up through METCM zone 26 (19–20 km) and through all METB3 zones (through zone 15 or 16–18 km). Since METCM and METB3 zones are in heights above ground level (AGL), the maximum zone may be less than 26 (METCM) or 15 (METB3) for sites with higher elevations. For example, the Amarillo, Texas, site has an elevation of 1099 m and as a result the maximum METCM zone was 25 (18–19 km). Since the METB3 extends only up to 18 km, a complete message was produced. In many cases, the RAOB covered all or nearly all 32 zones of the METCM from the surface though zone 31. However, comparisons were only made through zone 26, the maximum zone from the WRF-based profiles. At times, the RAOB ended at heights less than 20 km and even below 18 km resulting in METCMs or METB3s with fewer than 27 or 16 zones, respectively. The lower zones contained all the cases, that is, 131 samples each. However, since comparisons between the WRF output and RAOB values ended at the highest RAOB- or WRF-based zone (whichever was lower), there are fewer samples at higher zones. The number of samples is given later in the report (in Tables 1 and 2 in Section 3 for the METCM and METB3, respectively).

The sites selected were in both the northern and southern hemispheres, and included tropical, middle, and high latitude locations. They cover diverse climatic, seasonal, and geographical conditions. Appendix B contains a list of the 52 sites used for this analysis. Some sites such as the ones in the United States and Australia were used more than once, while others such as those from South America were only used once.

The variables selected were based on needs expressed by ARDEC, which focus on the METB3 and METCM variables of pressure, temperature, wind speed, wind direction, and the derived variable of density. In addition, vector wind speed difference was included to provide an indication of the combined effect of wind direction and speed differences. Pressure does not appear in the current MET error budget tables that have the METB3 format, but is in the METCM and is an important component of density and consequently was part of this study. The winds were analyzed by computing the difference in wind speed and calculating the vector difference between the 2 horizontal wind vectors derived from wind speed and direction in the 2 METCMs. This latter quantity is referred to as the vector wind speed (VW) difference in this report. VW difference normally is a better indicator of wind differences with respect to the effect on ballistic trajectories, since even a fairly small wind direction difference could have a noticeable impact if the wind speed is high. Also, note that all VW differences are necessarily positive and hence MD and MAD will be identical. Also, since METCMs have virtual temperature, those values were used instead of sensible temperature. For density calculations, virtual temperature provides more accurate values, especially in regions of higher humidity often found at or near the surface. Nevertheless, at higher altitudes or drier geographical regions, the difference between sensible and virtual temperature most often is very small. Differences of the variables were computed between the WRF and RAOB METCMs and METB3s for each zone for each case (i.e., 1 sample). For all cases, the computed statistical variables were MD, MAD, SD, and RMSD, plus the sample size for each zone.

2.2 Generation of Statistics from MET Messages

Processing the various model and sounding messages and determining the statistics from these data involve several steps. The initial step is to load the data into a Microsoft Access database. The second step is compute the bias errors for the appropriate model and sounding comparisons. The final step is to use Microsoft Excel to pivot the raw bias data into the desired error (i.e., difference) statistics. Appendix C has the explicit formulas used.

The first step in the process is loading the data into Microsoft Access. A custom Visual Basic for Applications (VBA) script was created that would read the model-based output and corresponding sounding data for each message type (METCM or METB3), output type (model or sounding), and date/time indicator. Based on message and output type, individual tables were created in Access that corresponded to all of the data for a given message/output type and included the data represented in natural units (scaling removed) along with station ID, date, time, and line or zone information. This processing step created the raw data for the bias calculations.

The second step employed Access to compute bias data from the raw data via the use of the Standard Query Language (SQL) inherent in databases. Noting that the bias data are the differences between model and sounding at each line or zone value, we link the model and sounding data for a given message type (for example, METB3) together using a SQL INNER JOIN, where the JOIN links the model and sounding tables by location, date, time, and line. This step ensures that the bias data are correctly computed for each message type. This creates a table organized by location, date, time, and line for a given message type that contains the bias data for each point compared. A SQL SELECT query transforms this table into the data table from which we compute the statistics. This step also adds in some supplementary calculations to facilitate pivot operations in Excel, which are used in the next step to compute the range of statistics desired and include the absolute value and square of the bias data.

The final step employs Microsoft Excel to create pivot tables that encapsulate the statistics organized in tabular form as presented in the next section. In this way, we can pivot on the raw bias data and compute the average by line to arrive at the mean deviation or MD per line. Using the raw and supplementary data developed in step 2, we can create the range of statistical measures described in Appendix C. In practice, where the original data were given in coded units, we add in a small fourth step using Excel to rescale the bias statistics back into the original form, that is, if the data were originally coded as, for example, temperature * 10 and MD was computed for temperature, the data presented in the following section would be represented as MD * 10.

One final note regarding wind difference computations. These differences are computed in terms of the easterly (U) and northerly (V) flows. This allows us to compute the VW bias as

$$VW_{bias} = \sqrt{(U^{WRF} - U^{RAOB})^2 + (V^{WRF} - V^{RAOB})^2}, \qquad (1)$$

in addition to independent calculations on wind speed and direction.

3. Results

Table 1 contains statistical summaries for the METCM variables in each individual zone, for all zones, and for all cases, and includes the sample size. The decrease in number of samples from the 131 cases for higher zones is due to the data in some RAOBs or WRF profiles ending or becoming incomplete before reaching the upper boundary height of these higher zones.

An initial look at a subset of the data showed high values of pressure differences. These large differences mostly arose from the differences in elevation between the actual height (MSL) at the RAOB site and the height derived from the WRF model's terrain database. To at least partially account for the elevation differences, we adjusted the surface elevation of the sounding (WRF or RAOB) with the lower value to that of the higher one, but did not change the sounding itself. Then the software interpolated the surface values from the sounding with the lower surface height (MSL) so that it started at the revised ("new") elevation. For example, if the WRF sounding had an elevation of 5 m and the RAOB had one of 40 m, the WRF sounding would be modified so that the output for the METCM or METB3 would begin at 40 m MSL. Interpolation is preferred over downward extrapolation from the surface values of the sounding with the higher surface elevation since such extrapolation requires assumptions such as a standard temperature lapse rate or no change in wind direction. Thus the accuracy of an interpolated sounding most likely will be better compared to one that is extrapolated.

Table 2 contains statistical summaries for the METB3 variables in each individual zone for all zones for all cases and includes each zone's sample size. The statistics in the current RAOB-based tables (Appendix A) are different from those in WRF-based (or based on another model) tables. The total error (or difference) of the current RAOB-based tables is the square root of the sum of the squares of the individual errors (i.e., instrument error, time staleness error, and distance staleness error), where each of those errors are assumed to be independent of the others. While instrument errors are not directly applicable to model-based profiles, if observations are assimilated into a model then the instrument errors can contribute to the model error (this WRF-based study did not include the assimilation of observations). The distance staleness error for the RAOBs refers to the distance between the balloon launch site and the location of application (e.g., the horizontal midpoint of the trajectory). Model-based profiles have a related source of error in that while the trajectory is impacted by the weather along a curved line, the model provides predictions of the weather in boxes as defined by the model's 3-D grid;

variations within any given box are not represented. Time errors can apply to both RAOB and model-based profiles; the difference between the time of the trajectory and that of the RAOB or the time represented by the model output can result in differences between the estimate of the weather at the trajectory and the actual weather at the trajectory. A major source of error in a model comes from the accuracy of its initial conditions. During the first part of the model simulation, error may decrease as realistic structures are "spun-up" by the model that were not represented in the initial conditions. Additionally, data assimilation may be applied and result in lower error than would be present without data assimilation. However, in general, the error grows with time. This growth depends on aspects such as the accuracy of the numerical schemes, the fidelity of the representations of atmospheric physical processes, and the accuracy of the boundary conditions. Model error also depends on the resolution of the model; higher resolution is able to better resolve underlying terrain as well as atmospheric processes. Stauffer (2013) provides further details on sources of uncertainty in NWP. Although there are differences between what is represented by the model-based RMSD values of Table 2 and the RAOB-based "total error" values in Appendix A, they may be compared in that both are representative of the total error or difference in the weather parameters produced by a NWP model and a RAOB, respectively.

The WRF and RAOB temperature and density are converted to percentage of the respective standard atmosphere value prior to the calculation of the statistics. The standard atmosphere for METB3 messages may be found in STANAG 4061 (2000) and FM 3-09.15 (2007), and is taken from the 1976 International Civil Aviation Organization atmosphere using geopotential heights. Nearly all the RMSDs are smaller than the total errors in the 2.0-h table and many are smaller than the respective values in the 0.5-h table. The exception is the wind speed for line 2, which is somewhat larger than the respective value in the 2.0-h table.

Table 1 Statistical quantities for the METCM by row for all 131 cases with respect to the differences from the RAOB values. Comparisons were made up to the maximum METCM zone covered by WRF and RAOB. The variables were differences in pressure (mb or hPa), virtual temperature (K*10), wind speed (kn), and wind direction (10s of mil).

		Pressure (hPa)				Virtual Temperature (K*10)				Wind Speed (kn)				Wind Direction (tens of mils)			
Line	Samples	MD	MAD	SD	RMSD	MD	MAD	SD	RMSD	MD	MAD	SD	RMSD	MD	MAD	SD	RMSD
0	131	-0.19	1.05	1.47	1.48	-5.7	19.1	24.6	25.1	2.29	3.22	3.92	4.52	24.06	83.39	117.49	119.49
1	131	-0.27	0.98	1.40	1.42	-4.5	14.5	18.1	18.5	2.60	3.92	4.57	5.24	12.63	55.53	84.20	84.83
2	131	-0.19	0.88	1.32	1.33	-1.9	11.3	14.3	14.4	0.73	4.03	5.34	5.37	13.76	42.30	66.28	67.44
3	131	-0.10	0.77	1.07	1.07	-2.0	8.1	10.4	10.5	-0.10	3.38	4.92	4.90	-5.26	44.71	73.34	73.24
4	131	-0.14	0.67	0.99	1.00	-0.6	7.6	9.6	9.6	-0.01	3.46	4.98	4.96	-3.44	35.59	53.63	53.54
5	131	-0.15	0.62	0.94	0.95	0.5	7.7	9.8	9.7	-0.32	3.82	5.40	5.39	-8.68	29.66	47.94	48.54
6	131	-0.05	0.60	1.05	1.04	0.5	8.0	10.1	10.1	-0.56	3.74	5.24	5.25	-10.39	27.67	50.82	51.68
7	131	-0.09	0.60	0.97	0.97	-0.9	6.9	8.8	8.8	-0.71	3.96	5.35	5.38	-1.92	29.42	52.81	52.64
8	131	-0.15	0.55	0.91	0.92	-0.7	6.2	8.0	8.0	0.03	4.23	6.10	6.08	3.23	29.40	49.53	49.45
9	131	0.00	0.47	0.79	0.79	0.6	6.0	7.7	7.7	0.17	4.49	6.30	6.28	-7.57	23.19	33.77	34.48
10	131	-0.08	0.59	0.91	0.91	-0.2	5.1	6.7	6.7	-0.04	4.13	5.80	5.78	-4.86	20.97	34.14	34.36
11	131	-0.04	0.51	0.82	0.81	0.6	5.5	6.8	6.8	-0.48	4.50	6.16	6.16	-3.84	20.65	38.03	38.08
12	131	-0.12	0.55	0.84	0.85	0.3	5.5	7.4	7.4	-1.06	4.68	6.72	6.78	-1.07	17.45	37.25	37.12
13	131	-0.03	0.47	0.76	0.76	-0.9	6.4	9.9	9.9	-1.28	4.18	5.80	5.91	-1.73	19.04	38.83	38.72
14	131	-0.08	0.53	0.78	0.79	-1.9	6.8	11.5	11.7	-1.02	4.41	6.14	6.20	1.02	13.44	20.71	20.66
15	131	-0.03	0.46	0.82	0.82	0.2	6.9	12.3	12.3	-1.22	4.46	6.27	6.36	3.18	14.94	28.42	28.49
16	131	-0.02	0.43	0.78	0.78	2.7	7.9	12.2	12.4	-1.60	4.89	6.99	7.15	1.44	11.76	18.65	18.64
17	130	0.05	0.39	0.82	0.82	6.4	10.3	13.0	14.4	-1.72	4.52	6.09	6.31	3.63	12.23	19.86	20.12
18	130	0.09	0.42	0.81	0.81	5.2	11.0	14.7	15.5	-1.61	4.58	6.51	6.68	4.15	10.48	17.47	17.90
19	128	-0.01	0.27	0.72	0.71	-2.9	10.8	14.5	14.7	-0.52	5.09	8.10	8.09	0.33	10.08	13.71	13.66
20	127	0.02	0.35	0.79	0.79	-2.8	9.3	12.6	12.9	-0.34	4.87	8.86	8.83	-1.62	9.23	14.83	14.86
21	125	0.04	0.25	0.65	0.65	-1.1	10.4	15.2	15.2	0.55	4.84	9.93	9.91	-2.22	11.53	21.03	21.06
22	120	0.05	0.23	0.63	0.63	1.0	10.4	17.2	17.2	-0.30	4.60	9.02	8.98	3.18	20.94	41.38	41.33
23	116	-0.04	0.22	0.69	0.69	1.9	10.8	19.6	19.6	-0.72	4.32	7.75	7.75	-8.15	21.59	45.17	45.70
24	112	-0.06	0.19	0.67	0.67	0.2	11.5	19.0	18.9	0.18	4.30	7.64	7.61	5.38	32.93	66.54	66.46
25	106	-0.04	0.15	0.39	0.39	-3.6	8.7	10.6	11.1	1.14	4.24	6.91	6.97	3.05	25.29	45.89	45.77
26	72	-0.04	0.13	0.35	0.35	-3.6	10.6	13.0	13.4	0.97	4.47	7.19	7.20	-6.26	27.21	46.28	46.39

Table 2 Statistical quantities for the METB3 by row for all 131 cases with respect to the differences from the RAOB values. Comparisons were made up to the maximum METB3 zone covered by WRF and RAOB. The variables were differences in density (% standard), temperature (% standard), and wind speed (kn).

		Density (% Standard)				Temperature (% Standard)				Wind Speed (kn)			
Line	**Samples**	**MD**	**MAD**	**SD**	**RMSD**	**MD**	**MAD**	**SD**	**RMSD**	**MD**	**MAD**	**SD**	**RMSD**
0	131	0.17	0.67	0.87	0.88	-0.20	0.67	0.86	0.88	2.29	3.22	3.92	4.52
1	131	0.13	0.52	0.65	0.66	-0.16	0.50	0.63	0.65	2.60	3.92	4.57	5.24
2	131	0.08	0.43	0.54	0.55	-0.08	0.40	0.51	0.51	1.10	3.76	4.94	5.04
3	131	0.06	0.34	0.42	0.42	-0.09	0.30	0.38	0.39	0.15	3.24	4.55	4.54
4	131	0.04	0.26	0.34	0.34	-0.05	0.23	0.30	0.31	0.16	2.80	4.20	4.18
5	131	0.03	0.23	0.30	0.30	-0.03	0.20	0.27	0.27	-0.07	2.85	4.48	4.46
6	131	0.01	0.19	0.25	0.25	-0.02	0.19	0.25	0.25	-0.18	2.74	4.25	4.24
7	131	0.00	0.17	0.22	0.22	0.00	0.16	0.21	0.21	0.02	2.82	4.43	4.41
8	131	0.00	0.14	0.19	0.19	0.00	0.13	0.18	0.17	-0.05	2.60	4.13	4.12
9	131	0.00	0.13	0.17	0.17	0.00	0.14	0.18	0.18	-0.38	2.56	3.97	3.98
10	131	0.01	0.12	0.18	0.18	0.00	0.14	0.18	0.18	-0.75	2.55	3.58	3.64
11	131	-0.01	0.12	0.18	0.18	0.00	0.14	0.18	0.18	-0.73	2.50	3.27	3.34
12	130	-0.04	0.12	0.16	0.17	0.00	0.14	0.18	0.18	-0.90	2.28	3.07	3.19
13	127	0.00	0.10	0.14	0.14	0.00	0.14	0.18	0.18	-0.54	2.13	3.00	3.03
14	120	-0.01	0.09	0.14	0.14	0.01	0.14	0.18	0.18	-0.46	2.16	3.20	3.22
15	112	-0.02	0.10	0.14	0.14	0.00	0.13	0.18	0.18	-0.42	1.99	3.13	3.14

For wind speed, Table 1 (METCM) shows a layer of maximum wind speed RMSD that includes zones 19–22 (12–16 km AGL). Higher wind speeds at those altitudes are reasonable since those heights are near the tropopause, which normally is not far from where jet streams often occur. Overall, the METB3 results are encouraging in that they suggest model-derived MET error budgets are generally within the range of values found in the RAOB based 0.5- and 2.0-h tables, and many values may be close to or smaller than the 0.5-h values. However, the fairly consistent drop off of wind speed difference in the METB3 table appears to be inconsistent with the aforementioned higher wind speed differences in the METCM table around zones 19–22. An initial investigation suggests that it may be related to the weighting of lower zones in the METB3, but a definitive answer remains to be determined.

As noted earlier, vector wind speed often can provide a better indicator of wind difference than regular wind speed alone, since it involves direction differences as well. Table 3 presents the vector wind speed difference RMSDs for the METCM and the METB3 zones. The respective values may be compared with the wind speed values in Tables 1 and 2.

Table 3 Vector wind speed difference RMSDs (kn) for the METCM and METB3 zones in Tables 1 and 2. Line number, midpoint height (m), and sample size are given as well.

METCM				METB3			
Line	Height	Samples	RMSD	Line	Height	Samples	RMSD
0	0	131	6.53	0	0	131	6.53
1	100	131	7.44	1	100	131	7.44
2	350	131	8.03	2	350	131	7.57
3	750	131	7.70	3	750	131	6.97
4	1250	131	7.24	4	1250	131	6.19
5	1750	131	7.12	5	1500	131	5.89
6	2250	131	6.91	6	2500	131	5.37
7	2750	131	7.70	7	3500	131	5.73
8	3250	131	8.52	8	4500	131	5.41
9	3750	131	8.46	9	5500	131	5.15
10	4250	131	8.05	10	7000	131	4.78
11	4750	131	8.38	11	9000	131	4.41
12	5500	131	8.40	12	11000	130	4.21
13	6500	131	7.70	13	13000	127	3.79
14	7500	131	8.37	14	15000	120	3.90
15	8500	131	8.48	15	17000	112	3.73
16	9500	131	9.30				
17	10500	130	9.20				
18	11500	130	9.65				
19	12500	128	9.51				
20	13500	127	10.36				
21	14500	125	11.21				
22	15500	120	11.73				
23	16500	116	9.79				
24	17500	112	9.28				
25	18500	106	8.27				
26	19500	72	8.62				

A further consideration is the comparison with coincident RAOBs. RAOBs provide the best readily available approximations to the real atmosphere. However, aside from instrument errors, there are spatial errors that arise from the drift of the radiosonde as it ascends and temporal errors that result from the time taken from launch to end of sounding (e.g., Seidel et al. [2011]) as, for example, when the balloon bursts. Thus, a RAOB represents a view of the atmosphere along a path defined by movement of the radiosonde in space and time. On the other hand, the WRF-based soundings represent vertical profiles constructed from a column of 3-km × 3-km "boxes" with different thicknesses at a specific time. Consequently, one cannot expect an exact match between WRF-and RAOB-derived METCMs, and neither will exactly match the real atmosphere. Though most often a RAOB yields a closer approximation to the real atmosphere, a coincident WRF-based sounding may be a closer fit for a specific time and place, at least for one or more variables over a part of the vertical extent.

4. Conclusion

This analysis for the estimation of the MET error budgets from numerical model output using open-source data produced statistics for the variables of interest for 131 cases using METCMs or METB3s generated from the WRF model output compared with those derived from coincident RAOBs. The MDs, MADs, SDs, and RMSDs of the difference values were computed for each METCM or METB3 zone that had data from the RAOB- and WRF-derived METCMs or METB3s, respectively, for up to 131 samples. All cases were included in the lower zones with a drop off in the number of samples at the higher zones due to some RAOBs that ended or had incomplete data before reaching the higher zone altitudes or WRF-derived profiles that ended before 20 km AGL. For the METB3, the values from this study suggest that the WRF-based METB3s mostly have values that are smaller than the respective ones for the current 2.0-h MET error budget tables and many are smaller than the ones from the 0.5-h table. However, more exact comparisons between values in the WRF- and RAOB-based tables are made more difficult due to uncertainties in the exact methodology used to create the RAOB-based tables.

Error in the context of this report refers to the difference between METCM or METB3 values computed using WRF output as the source of data and those computed from the coincident RAOBs. Since a RAOB is not actually derived from measurements of the atmosphere directly above a specified location on the ground at a specified time due to, for example, balloon drift and duration of ascent, a complete description of the MET error budget should also account for the potential error inherent in RAOB-derived METCMs or METB3s. The model-based error budgets presented here are based on a specific configuration of a specific model (WRF) and actual error budgets may vary depending on the model employed and the exact configuration used. Furthermore, these results represent an average over a variety of cases; the errors in a particular situation may vary substantially from those presented herein due to case-to-case variations.

Nevertheless, this analysis provides a basis for further work and a way forward for a more complete compilation of these statistics for a MET error budget based on numerical weather model output.

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Appendix A. Sample Meteorological (MET) Error Budget Tables

This Appendix presents 3 sheets listing the meteorological (MET) error budget tables for 3 staleness levels: 0.5 h and 10 km, which has the least error; 2 h and 20 km; and 4 h and 48 km (Tables A-1 through A-3). The tables show the error due to instrument error, time staleness error, spatial staleness error, and the total error from these 3 contributions. A complete set of MET budget data sheets were provided by the US Army Armament Research, Development, and Engineering Center in an unpublished document.[1] Time and distance staleness are listed on each table in the upper-left corner. The MET lines are those of the ballistic MET message for surface-to-surface fires (METB3). As noted in the upper-right corner of each table, the MET budget used the mean mid-latitude wind profile. Presumably, radiosonde observations (RAOBs) at different temporal and spatial separations from the verification RAOB are compared to the verification RAOB to calculate differences. The density and temperature values are converted to respective percentages of the 1976 International Civil Aviation Organization standard atmosphere. These tables were computed for the METB3 message and have METB3 units for the 3 variables listed (i.e., percentage of standard for density and temperature, and knots for wind). Note that the values for line 0 (not shown on these tables) are the same as for line 1.

[1]Met error in the delivery accuracy error budget. Picatinny Arsenal (NJ): US Army Armament Research, Development, and Engineering Center. Unpublished, 2013.

Table A-1 MET budget values for the listed time (0.5 h) and separation (10 km) staleness values

Time Staleness (hr) [0.5 to 12]	Separation (Distance) Staleness (km)
0.5	10

Mid Latitude Mean Wind Profile
Optimized for Annual Winds (FARMY-153-5)
NAVAIDS (MDS) Used for Instrument Error

	Density				Wind				Temperature			
Met Line	Instrument Error (%)	Time Staleness Error (%)	Distance (Separation and Balloon Drift) Staleness Error (%)	Total Error (%)	Instrument Error (kts)	Time Staleness Error (kts)	Distance (Separation and Balloon Drift) Staleness Error (kts)	Total Error (kts)	Instrument Error (%)	Time Staleness Error (%)	Distance (Separation and Balloon Drift) Staleness Error (%)	Total Error (%)
1	0.15	0.65	0.53	0.85	1.65	1.84	3.03	3.91	0.25	0.50	0.41	0.69
2	0.15	0.41	0.34	0.55	1.04	1.90	1.55	2.66	0.25	0.31	0.26	0.48
3	0.15	0.29	0.24	0.40	0.55	1.99	1.63	2.63	0.25	0.22	0.18	0.38
4	0.15	0.24	0.20	0.34	0.42	2.05	1.69	2.70	0.25	0.18	0.15	0.34
5	0.15	0.21	0.17	0.31	0.41	2.10	1.75	2.76	0.25	0.16	0.13	0.32
6	0.15	0.17	0.14	0.27	0.25	2.14	1.84	2.83	0.25	0.13	0.11	0.30
7	0.15	0.15	0.13	0.25	0.21	2.16	1.97	2.93	0.25	0.11	0.10	0.29
8	0.15	0.13	0.13	0.24	0.17	2.17	2.13	3.05	0.25	0.10	0.10	0.29
9	0.15	0.12	0.13	0.23	0.13	2.21	2.36	3.23	0.25	0.09	0.10	0.28
10	0.15	0.10	0.13	0.22	0.11	2.41	2.96	3.81	0.25	0.08	0.10	0.28
11	0.15	0.09	0.13	0.22	0.07	2.47	3.60	4.36	0.25	0.07	0.10	0.28
12	0.15	0.08	0.14	0.22	0.06	2.42	4.08	4.74	0.25	0.06	0.11	0.28
13	0.15	0.08	0.15	0.22	0.05	2.20	4.11	4.66	0.25	0.06	0.11	0.28
14	0.15	0.07	0.15	0.22	0.04	1.93	3.87	4.32	0.25	0.06	0.11	0.28
15	0.15	0.07	0.14	0.22	0.03	1.65	3.45	3.82	0.25	0.05	0.11	0.28

Table A-2 MET budget values for the listed time (2 h) and separation (20 km) staleness values

Time Staleness (hr) [0.5 to 12]	Separation (Distance) Staleness (km)
2	20

Mid Latitude Mean Wind Profile
Optimized for Annual Winds (FARMY-153-5)
NAVAIDS (MDS) Used for Instrument Error

	Density				Wind				Temperature			
Met Line	Instrument Error (%)	Time Staleness Error (%)	Distance (Separation and Balloon Drift) Staleness Error (%)	Total Error (%)	Instrument Error (kts)	Time Staleness Error (kts)	Distance (Separation and Balloon Drift) Staleness Error (kts)	Total Error (kts)	Instrument Error (%)	Time Staleness Error (%)	Distance (Separation and Balloon Drift) Staleness Error (%)	Total Error (%)
1	0.15	1.30	0.75	1.51	1.05	3.08	3.47	5.32	0.25	0.89	0.57	1.18
2	0.15	0.82	0.48	0.96	1.04	3.80	2.19	4.51	0.25	0.63	0.36	0.77
3	0.15	0.58	0.34	0.69	0.55	3.98	2.30	4.63	0.25	0.44	0.26	0.57
4	0.15	0.47	0.27	0.57	0.42	4.11	2.38	4.76	0.25	0.36	0.21	0.49
5	0.15	0.41	0.24	0.50	0.41	4.19	2.44	4.87	0.25	0.31	0.18	0.44
6	0.15	0.34	0.20	0.42	0.25	4.27	2.50	4.96	0.25	0.26	0.15	0.39
7	0.15	0.29	0.17	0.37	0.21	4.31	2.58	5.03	0.25	0.22	0.13	0.36
8	0.15	0.26	0.16	0.34	0.17	4.33	2.66	5.09	0.25	0.20	0.12	0.34
9	0.15	0.24	0.15	0.32	0.13	4.41	2.81	5.23	0.25	0.18	0.12	0.33
10	0.15	0.21	0.14	0.29	0.11	4.61	3.32	5.85	0.25	0.16	0.11	0.31
11	0.15	0.18	0.14	0.28	0.07	4.93	3.84	6.25	0.25	0.14	0.11	0.31
12	0.15	0.17	0.15	0.27	0.06	4.84	4.24	6.43	0.25	0.13	0.11	0.30
13	0.15	0.16	0.15	0.26	0.05	4.39	4.22	6.09	0.25	0.12	0.11	0.30
14	0.15	0.15	0.15	0.26	0.04	3.85	3.94	5.51	0.25	0.11	0.11	0.30
15	0.15	0.14	0.15	0.25	0.03	3.30	3.51	4.82	0.25	0.10	0.11	0.29

Table A-3 MET Budget values for the listed time (4 h) and separation (48 km) staleness values

Time Staleness (hr) [0.5 to 12]	Separation (Distance) Staleness (km)	
4	48	

Mid Latitude Mean Wind Profile
Optimized for Annual Winds (FARMY-153-5)
NAVAIDS (MDS) Used for Instrument Error

	Density				Wind				Temperature			
Met Line	Instrument Error (%)	Time Staleness Error (%)	Distance (Separation and Balloon Drift) Staleness Error (%)	Total Error (%)	Instrument Error (kts)	Time Staleness Error (kts)	Distance (Separation and Balloon Drift) Staleness Error (kts)	Total Error (kts)	Instrument Error (%)	Time Staleness Error (%)	Distance (Separation and Balloon Drift) Staleness Error (%)	Total Error (%)
1	0.15	1.84	1.16	2.18	1.65	5.20	3.89	6.70	0.25	1.41	0.89	1.68
2	0.15	1.16	0.74	1.38	1.04	5.37	3.40	6.44	0.25	0.89	0.56	1.08
3	0.15	0.82	0.52	0.98	0.55	5.63	3.56	6.69	0.25	0.63	0.40	0.79
4	0.15	0.67	0.43	0.81	0.42	5.81	3.67	6.89	0.25	0.51	0.33	0.66
5	0.15	0.58	0.37	0.70	0.41	5.93	3.75	7.03	0.25	0.44	0.28	0.58
6	0.15	0.47	0.30	0.58	0.25	6.04	3.83	7.16	0.25	0.36	0.23	0.50
7	0.15	0.41	0.26	0.51	0.21	6.10	3.88	7.24	0.25	0.31	0.20	0.45
8	0.15	0.37	0.24	0.46	0.17	6.13	3.92	7.28	0.25	0.28	0.18	0.42
9	0.15	0.34	0.22	0.43	0.13	6.24	4.03	7.43	0.25	0.26	0.17	0.39
10	0.15	0.29	0.19	0.38	0.11	6.81	4.49	8.15	0.25	0.22	0.15	0.37
11	0.15	0.26	0.18	0.35	0.07	6.97	4.80	8.46	0.25	0.20	0.14	0.35
12	0.15	0.24	0.17	0.33	0.06	6.84	4.97	8.46	0.25	0.18	0.13	0.34
13	0.15	0.22	0.17	0.32	0.05	6.21	4.76	7.82	0.25	0.17	0.13	0.33
14	0.15	0.21	0.16	0.30	0.04	5.45	4.35	6.97	0.25	0.16	0.13	0.32
15	0.15	0.19	0.16	0.29	0.03	4.66	3.83	6.03	0.25	0.15	0.12	0.32

Appendix B. World Meteorological Organization (WMO) Sites Used for the Meteorological (MET) Error Budget Analysis

Table B-1 presents the complete list of the World Meteorological Organization (WMO) sites used for the meteorological (MET) error budget analysis. A total of 52 sites were selected that cover a variety of geographical and climatological regions for all seasons, though the largest number of cases were from November 2015 through June 2016.

Table B-1 List of all WMO radiosonde observation (RAOB) stations used in the analysis of this report. Elevations are in meters above mean sea level (MSL).

Region	Station	Latitude (degrees)	Longitude (degrees)	Elevation (m)
US - Southwest	FGZ (Flagstaff, AZ)	35.23	-111.82	2192
	NKX (San Diego, CA)	32.85	-117.12	137
	TUS (Tucson, AZ)	32.23	-110.96	751
	VEF (Las Vegas, NV)	36.05	-115.18	697
	Wfo-PHX (Phoenix, AZ)	33.45	-111.95	384
US - East Coast	GSO (Greensboro, NC)	36.08	-79.95	270
	IAD (Dulles AP, VA)	38.98	-77.46	93
	MHX (Newport, NC)	34.78	-76.88	11
	RNK (Blacksburg, VA)	37.20	-80.41	654
	WAL (Wallops Is., VA)	37.93	-75.47	12
US-Mid-West	AMA (Amarillo, TX)	35.23	-101.70	1099
	DDC (Dodge City, KS)	37.76	-99.97	790
	LMN (Lamont, OK)	36.62	-97.48	317
	OUN (Norman, OK)	35.18	-97.44	345
	TOP (Topeka, KS)	39.07	-95.62	270
US-NE/Canada	ALB (Albany, NY)	42.69	-73.83	95
	GYX (Gray, ME)	43.90	-70.25	125
	WMW (Maniwaki, Quebec)	46.30	-76.01	189
US-Mountain	GJT (Grand Junction, CO)	39.11	-108.53	1475
	RIW (Riverton, WY)	43.06	-108.48	1703
	SLC (Salt Lake City, UT)	40.77	-111.95	1289
Germany	ETGB (Bergan)	52.81	9.93	69
	ETGI (Idar-Oberstein)	49.70	7.33	377
	ETGK (Kuemmersbruck)	49.43	11.90	418
	MEIN (Meiningen)	50.56	10.38	450
	STUT (Stuttgart)	48.83	9.20	321
South Korea	CHEJ (Cheju)	33.28	126.16	73
	HEUK (Heuksando)	34.68	125.45	69
	POHA (Pohang)	36.03	129.38	6
	RKJJ (Kwangju)	35.11	126.81	13
	RKSO (Osan AB)	37.10	127.03	52
Australia	YMML (Melbourne)	-37.66	144.85	119
	YPAD (Adelaide)	-34.95	138.53	4
Alaska	PADQ (Kodiak)	57.75	-152.50	34
	PAKN (King Salmon)	58.68	-156.67	8
	PANC (Anchorage)	61.16	-150.01	40
East Europe	BUDA (Budapest, Hungary)	47.43	19.18	139
	POP (Poprad-Gabivce, Slovakia)	49.03	20.31	706
	PRA (Prada-Libus, Czech -Rep)	50.01	14.45	304
	PRO (Prostejov, Czech -Rep)	49.45	17.13	216

Table B-1 List of all WMO radiosonde observation (RAOB) stations used in the analysis of this report. Elevations are in meters above mean sea level (MSL) (continued).

NE Brazil	FORT (Fortaleza)	-3.76	-38.60	19
	SBNT (Natal Aeroporto)	-5.91	-35.25	49
South Brazil	SBPA (Porto Alegre)	-30.00	-51.18	3
	SBSM (Santa Maria)	-29.72	-53.70	85
SE Brazil	SBFL (Florianopolis)	-27.67	-48.55	5
	SBLO (Londrina)	-23.33	-51.13	569
	SBMT (Marte Civ)	-23.52	-46.63	722
	SCBT (Curitiba Aeroporto)	-25.51	-49.16	908
Argentina	SAME (Mendoza)	-32.83	-68.78	704
Chile	SCSN (Santo Domingo)	-33.65	-71.61	75
South Africa	FAIR (Pretoria)	-25.91	28.21	1523
	FALE (King Shaka)	-29.61	31.12	109

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Appendix C. Error Calculations

This Appendix describes the specific calculations for computing the error (i.e., difference) statistics used throughout this report.[1]

The following are the definitions used.

X_i is the value of an observed meteorological variable, selected from a sounding or model output, expressed in natural units (e.g., K, or hPa).

Y_i is a particular instance of X_i stored as a coded meteorological variable in a sounding or model output file (e.g., Y_i might take the value of 10 * X_i, where X_i in this case represents temperature).

Let $X_i \ = \ k_j^{-1} \, Y_i$, where $k_j > 0$ is an appropriately chosen scaling factor that may depend on altitude but not on the observation itself. For the computer meteorological (MET) message (METCM) the factor k = 10 for temperature or virtual temperature where the units are tenths of a degree (e.g., 2915 instead of 291.5) and 0.1 for wind direction with units of tens of mils (e.g., 346 [rounded value] instead of 3458). Similarly for the ballistic MET message for surface-to-surface fires (METB3), k = 10 since the units are in tenths of a percent (e.g., 963 instead of 96.3).

Assume that both model and corresponding sounding data are scaled by the same value k_j; thus, the bias becomes

$$B_i = X_i^m - X_i^s = \ k_j^{-1} \, (Y_i^m - Y_i^s), \qquad \text{(C-1)}$$

where the superscripts m and s indicate a model or sounding value.

As noted previously, the term “deviation” is used to indicate the difference or departure of measured from model soundings.

With the bias now defined in terms of either natural or coded MET data, we can now define the following:

- Mean bias ≡ mean error ≡ mean deviation → MD
- Mean absolute error ≡ mean absolute deviation → MAD
- Sample standard deviation of the error ≡ sample standard deviation of the bias → SD
- Root mean square error ≡ root mean square deviation ≡ → RMSD

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[1] Australian Bureau of Meteorology. WWRP/WGNE joint working group on forecast verification research. Melbourne (Australia): Australian Bureau of Meteorology; 2015 Jan 26 [accessed 2016]. http://cawcr.gov.au/projects/verification/.

- N to be the number of sample points under consideration.

The error statistics are computed using the following equations:

$$MD = \frac{1}{N}\sum_1^N B_i = \frac{k_j^{-1}}{N}\sum_1^N (Y_i^m - Y_i^s)\ . \qquad \text{(C-2)}$$

$$MAD = \frac{1}{N}\sum_1^N |B_i| = \frac{k_j^{-1}}{N}\sum_1^N |Y_i^m - Y_i^s|\ . \qquad \text{(C-3)}$$

$$SD = \sqrt{\frac{1}{N-1}\sum_1^N (B_i - \bar{B})^2} = \frac{1}{k_j}\sqrt{\frac{\sum_1^N \left[Y_i^m - Y_i^s - \frac{1}{N}\sum_1^n (Y_i^m - Y_i^s)\right]^2}{N-1}}\ . \qquad \text{(C-4)}$$

$$RMSD = \sqrt{\frac{1}{N}\sum_1^N B_i^2} = \frac{1}{k_j}\sqrt{\frac{\sum_1^N (Y_i^m - Y_i^s)^2}{N}}\ . \qquad \text{(C-5)}$$

List of Symbols, Abbreviations, and Acronyms

AGL	above ground level
ARDEC	US Army Research, Development, and Engineering Center
MAD	mean absolute difference or mean absolute deviation
MAE	mean absolute error
MD	mean difference or mean deviation
MET	meteorological
METB3	ballistic meteorological message for surface-to-surface fires
METCM	computer MET message
MSL	mean sea level as in above mean sea level
NWP	numerical weather
NATO	North Atlantic Treaty Organization
PVM	Profiler Virtual Module
RAOB	radiosonde observation
RMSD	root mean square difference or root mean square deviation
RMSE	root mean square error
SD	standard deviation
STANAG	NATO Standardization Agreement
WRF	Weather Research and Forecasting
VW	vector wind speed

1 DEFENSE TECHNICAL
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RDRL CIO L
RDRL IMAL HRA RECORDS MGMT

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4 DIRECTOR
(PDF) US ARMY RSRCH LAB
RDRL CIE
J COGAN
J SMITH
P HAINES
B REEN

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