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Generation of a Gridded Meteorological Message (METGM) from Weather Research and Forecasting (WRF) Output Files and Initial Results

by J Cogan

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14. ABSTRACT
Effective support for deep-fire missions requires a more accurate knowledge of atmospheric conditions than is presently available, especially for longer ranges. One key capability already in use by several NATO countries is the gridded meteorological (MET) message (METGM). The METGM consists of numerical weather prediction (NWP) output data that are presented in a standard format. The 3-D METGM (4-D if more than one forecast time) provides better MET information than the older 1-D computer MET message (METCM). Countries that adopted the METGM can convert NWP output into a METGM, but software developed for specific systems may not be readily available. Furthermore, development of conversion software has centered on European models and NWP formats used for models from major centers. There is no widely available capability to convert mesoscale model data using the Network Common Data Form format. This report presents a means to convert Weather Research and Forecasting model output in NetCDF format into a METGM. The METGM output of the current report is suitable for computation of firing solutions, but may not have all the optional output necessary for additional applications.

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1. Introduction

Effective support for deep-fire missions requires a more accurate knowledge of atmospheric conditions than is presently u. Many nations already have cannon artillery that can outrange current US systems. Information on the current capabilities of US and foreign artillery systems may be found on a variety of publically accessible websites, some of which are listed in Section 8. A comparison of foreign tactical missile systems on open sites (e.g., Military-Today.com [2019]) suggests there may be a disparity with respect to missile systems as well. To address this situation, the United States has programs underway that should begin to have an effect over the next several years.

For longer artillery ranges, the need for accurate meteorological (MET) information increases. Many NATO countries, and potential adversaries, have adopted newer, more effective means to obtain required MET information. More modern capabilities normally produce more accurate MET input to fire control systems. One of the key capabilities already in use by several NATO countries, but not yet adopted by the United States as of the writing of this report, is the use of a gridded MET message (METGM). The METGM consists of numerical weather prediction (NWP) output data that are presented in a standard format as described in a NATO document, STANAG 6022 MET (2010). The 3-D METGM (4-D if more than one forecast time is used) provides better MET information than the 1-D computer MET message (METCM) described in STANAG 4082 MET (2012) still in use by US forces. The METGM accounts for variability in MET variables in all spatial dimensions plus time if the model data have more than one forecast time. On the other hand, the METCM assumes horizontal homogeneity and is for one time only. For shorter ranges (e.g., 15 km), the difference in a firing solution between using a METGM to obtain the required MET information and using a METCM is small. However, for longer ranges (e.g., 70 km), the difference can be large, especially if over mountainous regions.

The countries that have adopted the METGM have the ability to convert NWP output into a METGM, but software developed for specific systems may not be readily available elsewhere. Furthermore, development of conversion software within NATO has centered on European models and NWP formats (e.g., GRIB2) used for global and larger regional models such as models from the European Center for Medium-range Weather Forecasting (ECMWF) and other major centers. However, there is no widely available ability to convert mesoscale or regional model data using the Network Common Data Form (NetCDF) format. This report presents a means to convert Weather Research and Forecasting (WRF) model output in NetCDF format into a METGM. It involves two primary steps. The first converts WRF output into a text file with a specified format and the second converts the text file into a METGM. The WRF text output may have the vertical coordinate as height above ground level (AGL) or pressure.

In this report, the emphasis is on the version with height as the vertical coordinate since the one using pressure often does not replicate the WRF output as well as the height version for more complex or higher terrain. Information on WRF may be found at https://www.mmm.ucar.edu/weather-research-and-forecasting-model and the included links. The METGM output of the current report is suitable for computation of firing solutions, but may not have all the optional output necessary for additional applications.

2. Procedure Outline: Bash Scripts

The first part of the process for generating a METGM from a WRF output file is to produce a text file version of the WRF file. A Bash script, wrf2text.sh, calls in turn an NCAR Command Language (NCL) script, wrf2textgmh.ncl (height vertical coordinate) or wrf2textgmp.ncl (pressure vertical coordinate), and a Python 3 script, wrftexth.py (height vertical coordinate) or wrftextp.py (pressure vertical coordinate). Appendix A contains a high-level flowchart of wrf2text.sh (Fig. A1) and Appendix B has its source listing via an attached file in in the PDF attachment pane. The resultant text file becomes the input file for a FORTRAN program originally written in Germany (Weber 2002a) to process Global Forecast System (GFS) text output. Here the emphasis is on height (AGL) as the vertical coordinate, as noted previously. The NCL script converts the parts of the WRF file that are relevant for a METGM into a text file for each WRF forecast time (one time slice). The Python 3 script further modifies the text output from the NCL script and combines output files for up to nine time slices.

The Bash script is run by typing its name preceded by "./".

```
./wrf2text.sh
```

The script queries the user for whether the run is the first one or not. If "yes" or "y" is entered, the output text file is deleted to avoid appending multiple sets of output that could have, for example, different domains. The user then decides whether the output will have height AGL (h) or pressure (p) as the vertical coordinate. The next query asks for the number of time slices (1 to 9 in the current version). The next request asks the user whether to (option 1) produce text in the format for the FORTRAN program, plus output for the subdomain in a tabular format for easier human reading, or (option 2) output for the entire domain in the tabular format.

Option 2 may be useful for checking the data values within the WRF output without proceeding through the entire process, but the file can be very large. The script then queries the user for the input WRF file's name, including the path if not in the same directory. If the user wanted text output in the format for the FORTRAN program, the NCL script is called and produces information on the size of the WRF domain in terms of the minimum and maximum latitudes and longitudes, then asks for the user to enter minimum and maximum values for a subdomain. The NCL script is called a second time with the coordinates and other information, and a text file is produced that is used as input to the Python 3 script. Note that the NCL program will run up to eight more additional times with respective queries for input filenames depending on the number of time slices requested.

The Bash script then asks the user for a text output filename. After entering the name, the Python 3 script is called, which produces the final text output, and the Bash script ends. The intermediate output files from the NCL script have names corresponding to the number of files, that is, gm_text1, gm_text2, …, gm_text9 for 1 to 9 model forecast times. The text table output from the NCL script for option 1 or 2 has the name wrf_text. The user provides the name of the final text output file (e.g., locationA_text).

A second Bash script, ascii2metgm.sh, may be used in the generation of the METGM. It is run by typing its name preceded by "./".

```
./ascii2metgm.sh
```

This script calls the FORTRAN program, metascii2metgm, which converts the text file generated by wrf2text.sh into a METGM with four dimensions (x,y,z,t) where t is time. The script queries the user for the name of the input file (e.g., locationA_wrf-text). The input file is copied to ncl2text.txt, which is the "standard" name of the input for metascii2metgm. This FORTRAN program ingests some of the runtime parameters (e.g., center longitude and latitude) from a separate text file, gm_parameters. That file holds several parameters that may be changed by the user, such as the grid spacing as well as a list of METGM levels.

The aforementioned Bash scripts were combined into one that calls the same included NCL and Python 3 scripts, and the same FORTRAN program. The included scripts and the program should be in the same directory as the combined Bash script, wrf2metgm.sh. The combined script is run by typing its name preceded by "./".

```
./wrf2metgm.sh
```

The requests to the user are much the same except that the option for generation and output of a file of text tables (wrf_text) for the entire domain is eliminated since it is not needed for generation of a METGM. Also, this script produces the "standard" text filename for the input to metascii2metgm and consequently there is no request for the text filename. The FORTRAN program also prints text information to the screen that is redirected to a file (screenoutput). An additional query after screenoutput is produced asks if the user wants to view the text information before the script ends via the vi editor. This text output is useful as a check on the operation of the program and it contains the output filename. The user may view the file afterward using vi or another editor, but should save it to a file with another name before running the script again since the screen output will be overwritten.

3. Included Scripts and Programs

The aforementioned Bash scripts call an NCL script, a Python 3 script, and a FORTRAN program. These scripts and programs perform the main work of the overall software set.

The following subsections briefly describe those components and flowcharts indicating the main sections of each may be found in Appendix A. An additional FORTRAN program may be used to extract METGM profiles for comparison with profiles extracted directly from the WRF output. Appendix A also has a flowchart to illustrate the primary sections of that program. Appendix B contains source listings of the height coordinate versions of the NCL and Python 3 scripts as well as the Bash script as attached files in in the PDF attachment pane. The pressure coordinate versions of the scripts are almost the same except for those lines of code that relate to the choice of the vertical coordinate. The FORTRAN program processes input with either height or pressure as the vertical coordinate.

3.1 NCL Script

There are two NCL scripts, one for output with the vertical coordinate in geopotential height (m) and the other in pressure (hPa). Both scripts (wrf2textgmh.ncl and wrf2textgmp.ncl, respectively) have several main sections. The first one reads the WRF output file and extracts the variables of interest. Those variables include pressure (hPa), geopotential height (km), temperature (K), humidity (%), u, v, and w wind components (ms^{-1}), and sea-level pressure (hPa). The next major part converts the vertical coordinate of the extracted WRF data from its standard coordinate (e.g., sigma levels or for newer versions of WRF sigma levels near the surface changing to pressure levels nearer to the model top) to user-defined height AGL or pressure levels. Following the conversion to height or pressure levels, the script extracts a subdomain defined in terms of user-defined maximum and minimum latitudes and longitudes that may have a size from only a few grid points to almost the entire parent domain. The resultant subdomain data are processed in the output section that writes the data in a text format that becomes the input for the subsequent Python 3 script. In addition, the data for the subdomain are written to a separate file in a tabular format that is more readable. As an option, the user can skip the generation of output for the Python 3 script and go directly to the output section that produces only the tabular output file. This latter option may be useful for test purposes.

3.2 Python 3 Script

The Python 3 script has two versions, wrftexth.py and wrftextp.py, for text input from the NCL script with height (AGL) or pressure vertical coordinates, respectively. Both versions reformat some of the data, add some additional header information, and remove other header information not currently used in the generation of a METGM. It also combines up to nine text output files from wrf2textgmh.ncl or wrf2textgmp.ncl into a single file. The NCL script text output has the data for each variable by horizontal layer, that is, all x,y grid point values for each value of the vertical coordinate. The FORTRAN program requires data by grid point, that is, values for all vertical levels for each x,y grid point. Consequently, wrftexth.py or wrftextp.py reorders the data values for all of the 3-D variables (e.g., temperature, humidity). The 2-D variables such as terrain height and sea-level pressure are not reordered.

The script wrftexth.py or wrftextp.py may be run in a standalone mode, but generally is not recommended due to the extra work involved. The user would have to first modify the Bash script so that the output for each run for one to nine forecast times of the respective NCL script is saved. In that case, the user could have, for example, gm_text1 and gm_text2 for two forecast times. With those files in place, then in this example, one would run wrftexth.py:

```
python3 wrftexth.py gm_textoutput gm_text1 gm_text2
```

where gm_textoutput is the name of the output text file (input for the FORTRAN program) with the vertical coordinate in height (m) and gm_text1 and gm_text2 are input files produced by the NCL script for two WRF forecast times. The current version of the Python 3 script allows for one to nine input files. A similar procedure using wrftextp.py will produce an output text file with pressure (hPa) as the vertical coordinate.

3.3 FORTRAN Program

The FORTRAN program (metascii2metgm) converts the text output from the Python script into a METGM. As noted earlier, the program was originally developed in Germany (Weber 2002a) to provide METGMs from GFS model data. Further modification here has enabled it to ingest text files derived from WRF model data, incorporated additional changes to enhance the ease of use, and others to enhance or correct issues with the program. For example, it has an improved vertical aligning of METGM and input height levels for interpolation, and a different means to compute heights from pressure levels. The program handles text files that have height mean sea level (MSL), height AGL, or pressure as the vertical coordinate. The procedure for text files with pressure as the vertical coordinate requires the conversion of pressure levels to height levels (AGL) for each grid point. Then the program computes the mean value of each height level over the domain of the METGM. Pressure values are computed at each grid point using the profile of mean height values. The use of mean height values and multiple interpolations result in the procedure being less direct when using pressure as the vertical coordinate.

Perhaps the largest change to the program was the replacement of the subroutine that converts pressure levels to heights AGL. The new subroutine is completely rewritten and uses newly written FORTRAN functions. For example, the program now uses the standard hypsometric formula to obtain surface pressure from the input sea-level pressure and surface temperature, humidity, and elevation versus using a linear interpolation. Some other important changes include some to eliminate potential negative weighting values where they should always be positive. Others help prevent access to locations outside the bounds of the input data arrays, such as implementing a bounds check.

Values for many of the parameters for running the original program were defined within data statements and a few within the program code itself. Changes to one or more parameters required changes to data statements or the coding followed by recompilation. The current version of the program has most parameter values defined using a separate parameter file in text format (gm_parameters). For example, the METGM grid sizes and intervals are defined using values in the parameter file versus filling in lengthy data statements and then recompiling. Also, the first part of the output filename is in the parameter file, allowing the user to input identifying information such as the name of the region (e.g., EastCoast). Appendix A has a high-level flowchart of metascii2metgm.f (Fig. A-4) and Appendix B has an example gm_parameters file with typical values (Table B-1).

This program may be run easily in a standalone mode. The user manually copies the text file output from wrf2text.sh to a file named ncl2text.txt, which is the generic name used by the FORTRAN program. The data printed to screen are lengthy and may be saved by redirecting to a file named by the user, for example,

```
cp wrf_text_2019042300 ncl2text.txt
./metascii2metgm > screentextdata
```

where wrf_text_2019042300 is the name of the text file produced via wrf2text.sh and the file screentextdata contains the output otherwise printed on the screen from metascii2metgm. The current form of the output is name_datetime.gm (e.g., wrf_201904120600.gm), where "name" is defined by the user via the parameter file. Appendix B has an example gm_parameters file with typical values (see Table B-2).

3.4 Additional Program for METGM Analysis

The ability to extract data from a METGM is essential for proper evaluation of the output from the set of scripts and programs discussed earlier. Another FORTRAN program, readmetgm (Weber 2002b), reads a METGM and originally wrote output for a single grid point to the screen. The program was modified with respect to ease of use and printing of additional information for each grid point, and allow printing of data for multiple grid points. In the earlier version, data were extracted for one grid point that was defined in the code. Changing the grid point required recompilation. Also, the input filename (e.g., us-201901141500-wac) was "hard coded" within the program, and changing it required recompilation. In the current version, the user enters the number of the minimum and maximum x,y grid points into a parameter file named gmread_pars, and the user copies the METGM file to one with the standard name metgm_input before running the program. No recompilation is needed. Normally, the output would be redirected to a file since the program sends the output to the screen. There is no set filename and the user may choose whatever name is convenient. An example of the procedure follows:

```
cp wrf_201904120600.gm metgm_input
./readmetgm > textout
```

where the file textout holds information and data in text format extracted from the METGM (wrf_201904120600.gm, in this example).

4. Sample Output

Samples of the text output from the Bash script wrf2text.sh are presented as well as samples in text format extracted from a METGM by the additional FORTRAN program readmetgm. The METGM is produced by the FORTRAN program metascii2metgm from the wrf2text.sh text output. Samples of text output are presented for files with height as the vertical coordinate. The output data with pressure as the vertical coordinate have much the same format except for pressure and height. The differences are noted at the end of Section 4.1.

4.1 Input Files

The sample WRF output files are for a region centered over Toledo Bend Reservoir (TBR), Louisiana, with a 9-km grid resolution domain covering 25.33° to 37.55° latitude and –101.30° to –86.20° longitude. This large area includes ocean (Gulf of Mexico), lakes, non-complex ("flat") terrain over, for example, southern Mississippi, southern Louisiana, and east Texas, and complex terrain in parts of the northern half of the domain. Table 1 shows a section of the output of latitude, longitude, and terrain height for three model forecast times (aka time slices) for a subdomain covering approximately –97° to –89° longitude and 29° to 35° latitude. The initial forecast time was 2019-03-14-0600 (Coordinate Universal Time [UTC]), as seen in Table 1.

Table 1 WRF output data in text format in the form required for input to the program to convert text data to a METGM. Text for three consecutive WRF files is presented. The part shown contains header information: line 1 has the date and time of the first input WRF file (yyyymmddhhmm); line 2 has the size in terms of grid points (x or longitude direction and y or latitude direction), number of forecast times, and number of input variables (must equal 8); and line 3 has the forecast time hours (UTC). The following lines have longitude (decimal degrees), latitude (decimal degrees), and terrain height (m MSL).

```
201903140600
85 75 3 8
6.0           7.0          8.0
-97.0337    29.0187     57.313
-96.9413    29.0211     45.035
-96.8488    29.0234     33.903
-96.7563    29.0257     28.507
-96.6639    29.0279     25.420
-96.5714    29.0300     22.573
-96.4790    29.0320     21.583
-96.3865    29.0340     22.106
-96.2940    29.0359     22.270
-96.2015    29.0378     21.635
-96.1091    29.0395     21.263
-96.0166    29.0412     20.791
-95.9241    29.0429     19.091
-95.8316    29.0444     17.146
-95.7391    29.0459     15.251
-95.6466    29.0474     12.852
-95.5541    29.0487     11.230
-95.4616    29.0500      9.745
-95.3691    29.0513      6.422
-95.2766    29.0524      2.710
-95.1841    29.0535      0.602
-95.0916    29.0546      0.057
```

Table 2 illustrates a portion of the text output from wrf2text.sh that lists the model output geopotential height levels followed by their respective pressures for each grid point of the subdomain. Height values are in meters AGL.

Table 2 Part of WRF output data in the text format required for input to the program to convert text data to a METGM. Text for three consecutive WRF files is presented. The section immediately follows the longitude, latitude, and elevation data of Table 1. The first line shown has the number of data levels, "parameter number" (indicates the variable, in this case pressure), and a number indicating whether the data lines are based on (0) height (m) MSL; (1) height (m) AGL, which was used for this report; or (2) pressure (hPa). The following single column has the height levels (m) followed by three columns of pressure (hPa), one column for each forecast time. If only one forecast time is chosen then there is only one column of pressures. Data for all heights for the first horizontal grid point are shown followed by the first few data lines of the second.

```
23    7    1
    0.00
  100.00
  200.00
  500.00
 1000.00
 2000.00
 3000.00
 4000.00
 5000.00
 6000.00
 7000.00
 8000.00
 9000.00
10000.00
11000.00
12000.00
13000.00
14000.00
15000.00
16000.00
17000.00
18000.00
19000.00
 1001.148  1000.612  1001.905
  989.380   988.982   990.154
  978.064   977.646   978.815
  944.845   944.365   945.493
  892.112   891.605   892.394
  793.966   793.552   794.087
  704.422   703.962   704.080
  623.039   622.392   622.200
  549.558   548.870   548.469
  483.293   482.672   482.213
  423.489   422.912   422.460
  369.413   368.886   368.518
  321.036   320.582   320.272
  277.802   277.419   277.186
  239.412   239.033   238.887
  206.039   205.639   205.590
  176.474   176.127   176.167
  150.425   150.119   150.204
  127.814   127.536   127.583
  108.351   108.173   108.127
```

91.525	91.428	91.337
77.243	77.167	77.001
65.217	65.097	64.896
1002.596	1002.101	1003.115
990.824	990.479	991.362
979.484	979.121	980.006
946.226	945.773	946.619

The following sections for temperature (K), relative humidity (RH) (%), and u and v wind components (ms^{-1}) list the respective values for one to nine forecast times (three in the examples presented here), each section following a list of all the height levels (23) including the surface. If pressure is the vertical coordinate, a value of 2001 is used to indicate the surface for the program to convert text to METGM. For WRF output with height coordinates, all levels have values of the vertical (w) wind component ("surface" for wind is at 10 m), but for pressure coordinates the surface value is skipped (e.g., leaving only 22 values). Tables 3 and 4 present samples of the text output for temperature and the v wind component. The other data listings are similar and are not shown.

Table 3 Part of WRF output data in the text format required for input to the program to convert text data to a METGM. Text for three consecutive WRF files is presented. The temperature section immediately follows the pressure data of Table 2. Except for the number for the temperature parameter, 5, the first line is the same as in Table 2. The height levels also are the same as in Table 2 and are followed by temperature (K) values as shown for the three forecast times. Data for one grid point are shown.

294.740	294.612	294.546
294.247	294.033	294.021
293.958	293.628	293.438
294.170	293.419	292.693
293.966	294.342	293.578
289.063	289.065	286.920
280.668	280.085	279.413
274.852	274.089	272.553
268.646	268.515	268.080
262.076	262.012	261.546
254.504	254.270	254.214
246.523	246.503	246.639
238.902	239.016	239.111
232.845	232.684	232.903
228.781	228.140	228.592
223.868	223.678	224.364
217.791	217.717	218.359
211.427	211.243	211.499
207.767	208.107	207.165
205.677	206.177	205.812
201.464	202.468	201.290
201.906	201.380	199.534
201.906	201.380	199.534
201.380	201.181	200.550

Table 4 Part of WRF output data in the text format required for input to the program to convert text data to a METGM. Text for three consecutive WRF files is presented. The v wind component section immediately follows the u component data. The first line that follows the u component data contains numbers for the parameters as noted in Table 2, except that for the v component the indicator is 3. The heights for the v component are the same as for temperature and are not repeated in this table. The v component (ms^{-1}) values for the three forecast times for one grid point are shown.

6.304	6.958	5.181
13.469	14.664	12.128
15.991	17.172	14.203
19.911	21.696	17.490
12.773	13.421	14.336
1.548	2.484	5.149
-2.165	-3.634	2.567
7.323	7.284	5.306
11.692	12.848	13.591
12.421	14.376	15.077
12.085	13.001	12.993
11.189	11.040	10.564
9.960	10.160	10.119
9.796	11.089	11.827
10.993	12.960	13.199
12.685	11.837	12.511
11.306	10.897	10.979
5.872	5.517	6.794
4.543	4.874	3.527
8.047	10.174	6.943
9.517	8.878	11.104
6.543	7.854	8.534
5.431	5.593	4.749

The last section of text output contains values for sea-level pressure. Sea-level pressure has one level only, which is indicated by the surface indicator of 0.00 (2001.00 for pressure coordinate input). For this section, the “surface” is not the same as for the other variables, but instead indicates sea level. Table 5 presents a sample of this section for several grid points.

Table 5 Part of WRF output data in the text format required for input to the program to convert text data to a METGM. Text for three consecutive WRF files is presented. The sea-level pressure section immediately follows the w component data. Here the first line contains numbers for the parameters as noted in Table 2, except that there is only one level and the sea-level pressure indicator is 7. This indicator value is the same as for the pressures of Table 2, but the combination with 1 for the number of levels (sea-level surface only) and the position within the overall text file tells the conversion to METGM program that the data are for sea-level pressure.

```
1     7     1
     0.00
 1007.477  1007.056  1008.258
 1007.505  1007.126  1008.053
 1007.543  1007.187  1007.963
 1007.610  1007.256  1007.907
 1007.675  1007.333  1007.841
 1007.654  1007.399  1007.836
 1007.543  1007.442  1007.801
 1007.517  1007.508  1007.733
 1007.629  1007.424  1007.810
 1007.725  1007.379  1007.792
 1007.921  1007.367  1007.865
 1008.035  1007.410  1007.902
 1008.090  1007.485  1008.034
 1008.257  1007.562  1008.047
 1008.354  1007.637  1008.083
 1008.447  1007.659  1008.067
 1008.531  1007.798  1008.050
```

As noted earlier, the text files with pressure as the vertical coordinate have a similar format as those that use height for the vertical coordinate. The formats for latitude, longitude, and grid point elevation data are the same as with the height-based data (e.g., Table 1). The data sections for temperature, RH, wind components, and sea-level pressure are the same as well. The indicator in the header of each section for the vertical coordinate changes from 1 to 2. In addition, for pressure-based data 2001.00 is used to indicate the surface in the list of pressure vertical coordinates versus 0.00 for height-based data, and pressure values proceed from the highest value to the lowest. Table 6 shows a header line, pressure coordinate values, and heights (MSL) of those pressures for one grid point. The section of text output shown in this table immediately follows the longitude, latitude, and elevation data (Table 1). The surface value of height is not listed since it is the same as the elevation, and consequently there is no surface indicator. For the list of pressure values for the other data sections (e.g., Table 7), the surface indicator is the first value that appears.

Table 6 Part of WRF output data in the text format required for input to the program to convert text data to a METGM when pressure is the vertical coordinate. The values of the vertical coordinate pressures are followed by their respective heights for each grid point. Data for the first 16 levels for one grid point are presented. The section immediately follows the longitude, latitude, and elevation data of Table 1. The first line shown has the number of data levels, "parameter number" (indicates the variable, in this case height MSL), and a number indicating whether the data lines are based on (0) height (m) MSL, (1) height (m) AGL, or (2) pressure (hPa). The following single column has the input pressure levels (hPa) followed by one column of height MSL (m) since there was only 1 forecast time. Since the elevations are the surface heights, they are not repeated here and there is no surface indicator.

```
24    7    2
  925.00
  900.00
  875.00
  850.00
  825.00
  800.00
  775.00
  750.00
  725.00
  700.00
  650.00
  600.00
  550.00
  500.00
  450.00
  400.00
  350.00
  300.00
  250.00
  200.00
  150.00
  100.00
   70.00
   50.00
  742.183
  980.728
 1224.761
 1474.586
 1730.209
 1992.214
 2260.814
 2536.218
 2818.686
 3108.271
 3712.507
 4357.588
 5047.675
 5792.002
 6596.724
 7475.945
```

Table 7 Part of WRF output data in the text format required for input to the program to convert text data to a METGM when pressure is the vertical coordinate. In this sample, the values of the vertical coordinate pressures are followed by the first 10 respective temperatures for one grid point. The surface indicator is 2001.00.

```
25    5    2
 2001.00
  925.00
  900.00
  875.00
  850.00
  825.00
  800.00
  775.00
  750.00
  725.00
  700.00
  650.00
  600.00
  550.00
  500.00
  450.00
  400.00
  350.00
  300.00
  250.00
  200.00
  150.00
  100.00
   70.00
   50.00
  294.740
  295.770
  294.570
  293.216
  292.624
  291.081
  289.444
  287.684
  285.404
  282.784
```

The lowest pressure level (highest pressure) in the list is the highest value in the input list of vertical pressures that is less than the lowest surface pressure value in the requested WRF subdomain. For the data shown in Table 6, the highest value is 725 hPa and the lowest surface pressure over the subdomain is 744.6 hPa (the highest elevation over the same subdomain is 2583.2 m). Consequently, over complex terrain the other horizontal grid points (have higher surface pressures and lower terrain heights) require interpolation of surface pressure in the program over larger height differences, which may lead to greater differences between METGM and WRF surface pressure values. Other than the aforementioned differences, the format of the output text file is the same whether the vertical coordinate is pressure or height.

4.2 METGM Data in Text Format

The FORTRAN program readmetgm (Weber 2002b), as modified for the work of this report, extracts header information and profile data for selected grid points of the input METGM. The sample output presented herein was extracted from a METGM for the same location and times as the input data used for Tables 1–5 of the previous section (Table 8). The METGM grid had 21 × 21 horizontal (x,y) grid points with a grid spacing of 0.095° longitude and 0.081° latitude, and the domain center was at –93.0405° longitude and 31.1368° latitude. Those coordinates were chosen so as to best align with a specific grid point in the WRF text output data. All the output text headers have the same type of information though the specific values may change for different variables or parameters. The one exception is that the first line of the first header has the "number of parameters", which is the total number of output variables (e.g., heights; temperature; u, v, w wind components) in the METGM. For all headers, the letter m is the index value for the indicated parameter (variable) in the program and p is the standard parameter identifier within the METGM and may not be the same as m. The "number of points (time)" refers to the number of forecast times (i.e., number of time slices), and for terrain heights (first header), it is set to 1 since terrain remains the same for all forecast times. The timestep is the time in seconds between forecast times. However, for terrain heights (first header) the timestep is the value in seconds for 1 day and is really a placeholder since terrain heights normally do not change over the time of a METGM. The value for reference meridian is a place holder. The "identifier ref. level" refers to heights MSL (0) or AGL (1), and the "identifier vert. coord." refers to use of only one set of height levels for all grid points. Nominally, each grid point could have a different number of METGM heights, but normally heights for all grid points are the same. Table 8 contains header information and values for terrain heights (m MSL) for the grid points listed. The longitude and latitude in decimal degrees are listed after the grid point numbers (x and y in the output of this program represent grid point numbers). The index values written along with the output data lines were changed to base 0 to match output line numbers from programs that generate data profiles in text format directly from WRF output (Cogan 2017, 2019).

Table 8 Section of text output from the program to read a METGM and extract data for selected grid points. Many of the listed parameters are self-explanatory or are explained in the text. The line following the "Identifier vert. coord." denotes that the initial AGL height (= 0 m) has an output index of 0. The next line has the value of m and the time slice (e.g., 1 for first forecast time). The data lines are in groups of two that start with the words "Grid point". The first line has grid point numbers and longitude and latitude, and the second has the respective output line number (0) and terrain height MSL (m). The first 5 data line groups are shown.

```
Number of parameters:    8

m = 1  Parameter p =     0
Number of Points (z,x,y)          1         21         21
Number of Points (time)           1
Grid spacing (x,y)            0.095     0.081
Time step                  86400.00
Center Point (lon/lat)    -93.04050  31.16380
Reference Meridian         9999.000
Identifier ref. level          0.00
Identifier vert. coord.        1.00

 0  height =       0.00

m =  1  time slice =  1

Grid point (x,y,lon,lat):  10  10   -93.13566  31.08272
            0     102.000000

Grid point (x,y,lon,lat):  10  11   -93.13566  31.16380
            0     101.000000

Grid point (x,y,lon,lat):  10  12   -93.13566  31.24488
            0     100.000000

Grid point (x,y,lon,lat):  11  10   -93.04050  31.08272
            0     100.000000

Grid point (x,y,lon,lat):  11  11   -93.04050  31.16380
            0     99.0000000
```

The text output for pressure, temperature, RH, and wind components have the same format. Parts of the temperature and v wind component text are shown in Tables 9 and 10. As noted previously, the index values written along with the output data lines were changed to base 0 so as to coincide with data lines from programs that produce vertical profiles from the WRF output itself. This change allows for a clearer comparison between the METGM and WRF derived profiles. The header information for each variable contains the same type of data as in Table 8, but some of the values are different. For example, the values for m and "Parameter p" are different for each variable. The number of times ("Number of Points (time)") has the number of forecast times for these variables. The heights AGL (m) are listed following the header lines along with the data line number (base 0). After the height list, the m value is repeated along with the number of forecast times (aka time slices). A series of profiles of the variable with each profile preceded by a line with the grid point (x, y) and its longitude and latitude appear for all grid points in sequence for that forecast time. The last section of the text has the header and data for sea-level pressure (Table 11). The format is nearly the same as for terrain heights except that the total number of parameters (first line in Table 8) does not appear. In this case, sea-level pressure replaces terrain height and values are presented for all time slices.

Table 9 Section of text output for temperature (K) from the program to read a METGM and extract data for selected grid points. Many of the listed parameters are self-explanatory or are explained in the text. Only output for the header, heights, and part of the data for the first forecast time is shown.

```
m = 3  Parameter p =     5
Number of Points (z,x,y)        25        21        21
Number of Points (time)          1
Grid spacing (x,y)           0.095     0.081
Time step                  3600.00
Center Point (lon/lat)   -93.04050  31.16380
Reference Meridian        9999.000
Identifier ref. level         1.00
Identifier vert. coord.       1.00

 0  height =       2.00
 1  height =     100.00
 2  height =     250.00
 3  height =     500.00
 4  height =     750.00
 5  height =    1000.00
 6  height =    1500.00
 7  height =    2000.00
 8  height =    3000.00
 9  height =    4000.00
10  height =    5000.00
11  height =    6000.00
12  height =    7000.00
13  height =    8000.00
14  height =    9000.00
15  height =   10000.00
16  height =   11000.00
17  height =   12000.00
18  height =   13000.00
19  height =   14000.00
20  height =   15000.00
21  height =   16000.00
22  height =   17000.00
23  height =   18000.00
24  height =   19000.00

m =  3  time slice =  1

Grid point (x,y,lon,lat):  10  10   -93.13566  31.08272
```

```
             0     293.799988
             1     293.500000
             2     293.000000
             3     292.100006
             4     291.200012
             5     290.399994
             6     288.399994
             7     285.399994
             8     281.600006
             9     277.000000
            10     270.700012
            11     264.100006
            12     257.799988
            13     251.800003
            14     245.100006
            15     239.000000
            16     234.699997
            17     232.100006
            18     228.399994
            19     224.600006
            20     219.800003
            21     215.000000
            22     210.199997
            23     205.300003
            24     202.199997

Grid point (x,y,lon,lat):  10  11   -93.13566  31.16380
             0     293.899994
             1     293.500000
             2     293.000000
```

Table 10 Section of text output for the v wind component (ms^{-1}) from the program to read a METGM and extract data for selected grid points. Many of the listed parameters are self-explanatory or are explained in the text. Only part of the data for the first time slice is shown. The data level heights are the same, and the header values are the same except that m = 6 and p = 3.

```
m =  6  time slice =  1

Grid point (x,y,lon,lat):  10  10   -93.13566  31.08272
            0     7.59999990
            1     9.10000038
            2     11.6000004
            3     15.8999996
            4     20.1000004
            5     21.1000004
            6     15.5000000
            7     14.8000002
            8     9.69999981
            9     10.6999998
           10     14.1999998
           11     13.8999996
           12     14.3000002
           13     15.8999996
           14     13.8000002
           15     11.6000004
           16     10.6000004
           17     10.1000004
           18     6.90000010
           19     3.50000000
           20     2.70000005
           21     1.89999998
           22     1.70000005
           23     1.89999998
           24     2.29999995

Grid point (x,y,lon,lat):  10  11   -93.13566  31.16380
            0     7.80000019
            1     9.30000019
            2     11.8000002
```

Table 11 Extract data for selected grid points. Many of the listed parameters are self-explanatory or are explained in the text. The header and the data lines are similar to those for terrain height as shown in Table 8. However, the values of m and p are 8 and 7, respectively, and the height of 0 represents sea level. Sea-level pressure replaces terrain height in the data section. The first 5 data groups of the first forecast time are shown.

```
m =  8  time slice =  1

Grid point (x,y,lon,lat):  10  10   -93.13566  31.08272
            0     1009.79999

Grid point (x,y,lon,lat):  10  11   -93.13566  31.16380
            0     1009.59998

Grid point (x,y,lon,lat):  10  12   -93.13566  31.24488
            0     1009.40002

Grid point (x,y,lon,lat):  11  10   -93.04050  31.08272
            0     1009.90002

Grid point (x,y,lon,lat):  11  11   -93.04050  31.16380
            0     1009.70001
```

5. Comparison: METGM-WRF

METGM profiles of the atmospheric variables may be compared with the respective profiles generated from WRF output. The method for extracting and processing profiles of atmospheric variables from WRF is described in Cogan (2017, 2019) and the included references. In brief, a Bash script calls an NCL script originally written by Reen (2017) that extracts vertical profiles of relevant variables for a user specified grid point. The Bash script then calls a version of the C program described in Cogan (2017) to convert the extracted profiles into a sounding with a user defined vertical structure. Given the different interpolation methods and the need to interpolate the input WRF based data horizontally to METGM grid points, profiles nominally for the same latitude and longitude most often would have some differences. However for non-extreme atmospheric conditions, values from METGM and “directly” from WRF for the same variable at the same heights should be fairly close and have much the same trends. For example, a trend toward increasing u wind component with height in one should relate to a similar trend in the other. MET profiles from METGMs derived from WRF output that has height (AGL) as the vertical coordinate are examined first. Later some results are presented for METGM profiles derived from WRF output with pressure as the vertical coordinate and compared with profiles from the same location within the same WRF domain using height as the vertical coordinate.

5.1 Height as Vertical Coordinate

Figure 1 compares the vertical profile of pressure extracted from a METGM derived from WRF output for –93.5685° longitude and 31.0374° latitude with profiles "directly" extracted from that WRF output for the same grid point. The selected grid point was at the center of the METGM domain, using the data for the first forecast time (2019-03-14-0600) of the same domain (TBR) as used for the tables of the previous section. The METGM latitude and longitude grid intervals were chosen to be nearly equivalent to 9 km (the WRF grid interval), and the center latitude and longitude were chosen to be the same to 0.0001° at a WRF grid point not far from the center of the WRF domain. Consequently, the METGM and WRF grid points are very close. Larger differences in METGM and WRF grid intervals (i.e., grid resolution) and locations will lead to larger differences in the MET variables.

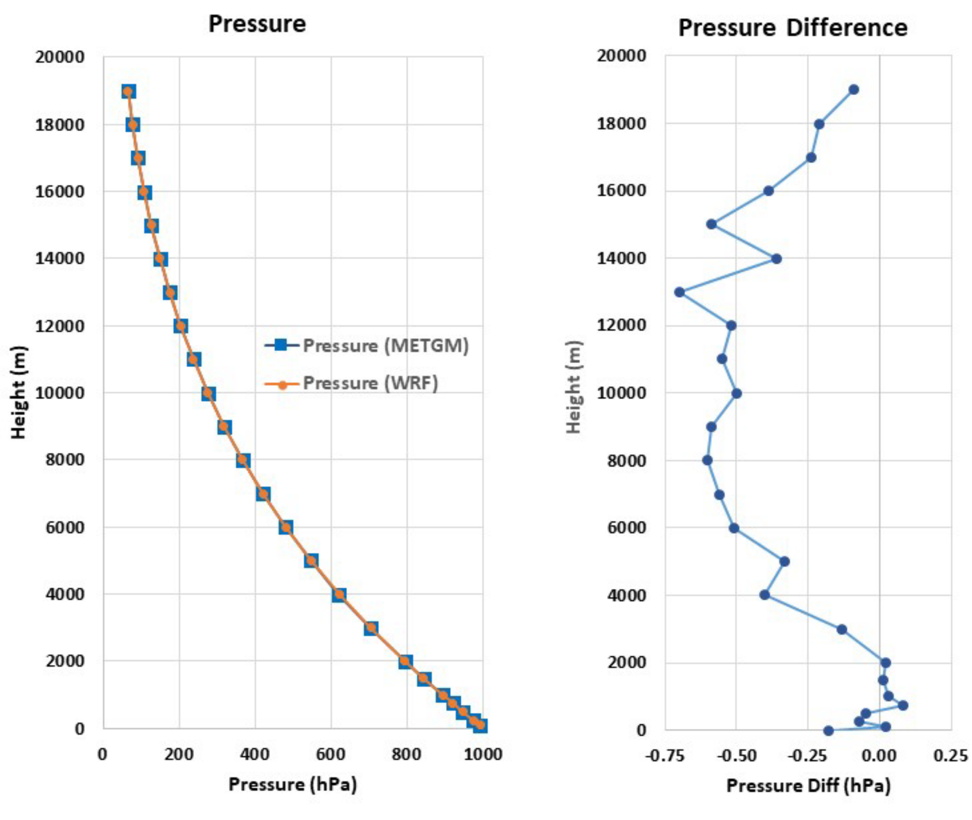


Fig. 1 Comparison of pressure (hPa) between METGM and WRF where the vertical coordinate of the input is height. In the scale of chart a), the curves essentially overlap. Chart b) presents the differences (METGM value – WRF value) at a different scale. The absolute differences remain below 0.25 hPa at all heights (maximum difference of 0.20 hPa), and at the highest levels as well as a couple of other levels the differences are not far from 0 (minimum differences ±0.01 hPa).

The comparison of temperature profiles for the same grid point has a similar outcome as with pressure, that is, the two profiles nearly overlapped. The absolute values of the differences only exceeded 0.1 K at 1 of the 25 levels including the surface. A maximum absolute difference (METGM value – WRF value) of 0.12 K occurred at 1500 m.

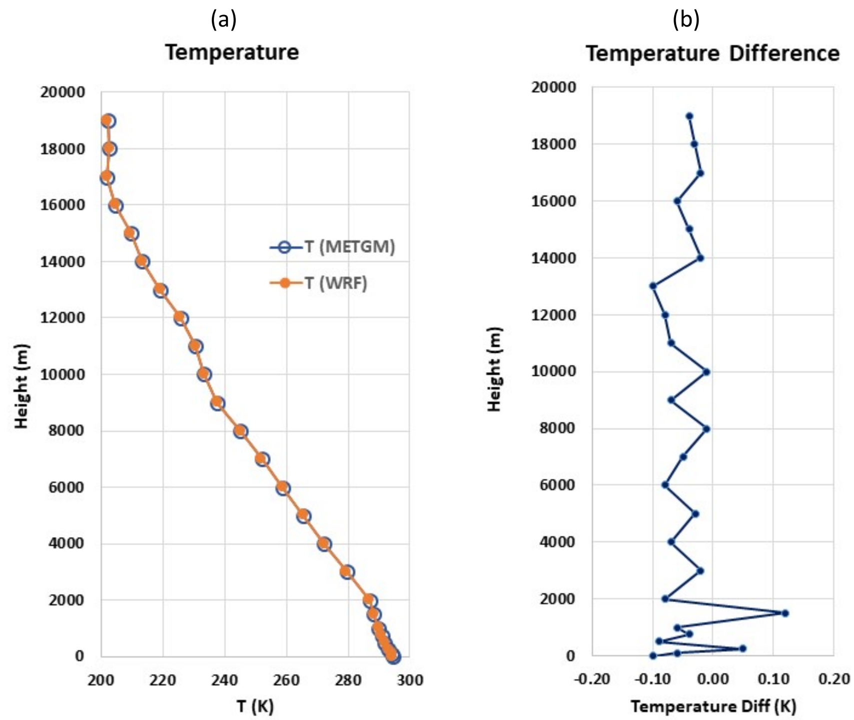


Fig. 2 Comparison of temperature (K) between METGM and WRF where the vertical coordinate of the input is height. In the scale of chart a), the curves essentially overlap. Chart b) presents the differences (METGM value – WRF value) at a different scale. All 25 data levels including the surface had absolute values of the differences less than or equal to 0.12 K (14 ≤ 0.05 K).

RH does show some greater differences. For the example of this report, all but 1 of the 25 levels had absolute differences less than 1.00%. That one level, 1500 m, had a difference (METGM value – WRF value) of –7.53%. Since RH is highly variable, the somewhat different interpolation methods, and the different nearby grid point locations of the METGM and WRF output used for interpolation, could lead to greater differences as compared to, for example, temperature. The outlier of –7.53% may not be as odd as it seems. The RH directly from WRF one grid point to the west had a RH of 55.0% and one to the east had a value of 78.5%. The RH from the METGM one point to the west was about the same (55.2%) as the WRF value, but the one to the east was less (67.7%) than the WRF value. For both the WRF and METGM profiles, the vertical difference from 1000 to 2000 m was about –83%. Given the large vertical, as well as horizontal, differences a small difference in interpolation could lead to a noticeable difference in RH.

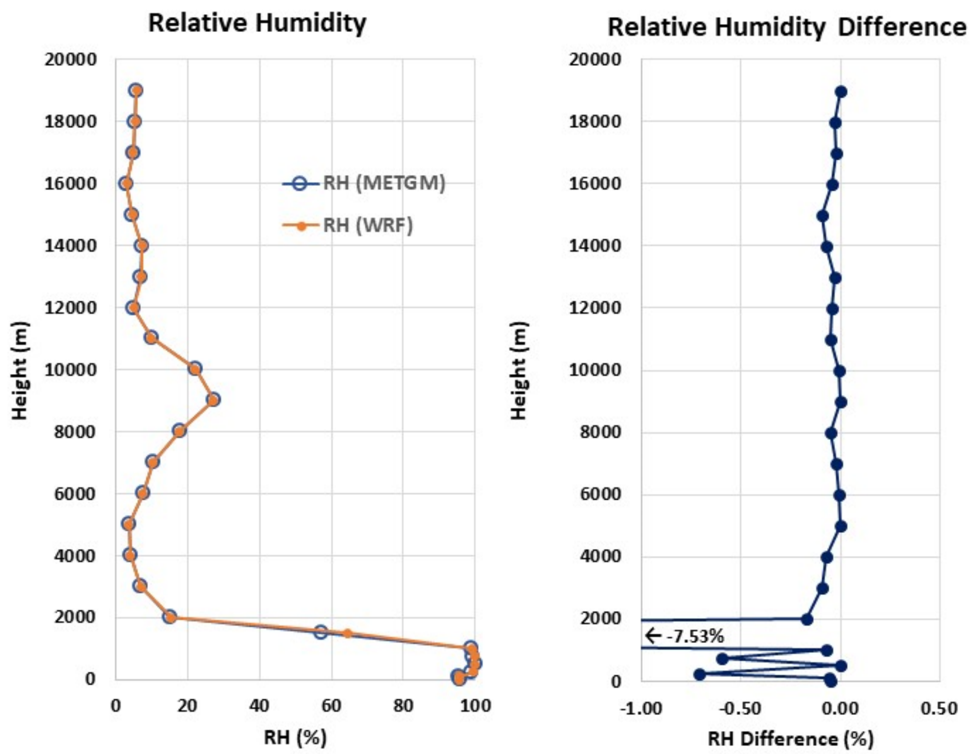


Fig. 3 Comparison of RH (%) between METGM and WRF where the vertical coordinate of the input is height. In the scale of chart a), the curves essentially overlap. Chart b) presents the differences (METGM value – WRF value) at a different scale. At most levels, the values from both sources are close to one another (< 0.1% and a few < 0.01%), but at two levels the differences (METGM value – WRF value) are noticeable (–0.71% at 250 m and –7.53% at 1500 m).

Figure 4 presents the u and v wind component comparisons on the same chart. The curves for the u component appear to nearly overlap at many heights at the scale of the chart, and the same holds for the v component. However, the differences (METGM value – WRF value) of the u and v components for a few data levels differed by noticeable magnitudes. The absolute values of the differences in u and v were <0.1 ms^{-1} for 22 and 21 of the 25 levels, respectively. The differences (METGM value – WRF value) with the largest magnitudes were 1.12 ms^{-1} (1500 m) and –1.43 ms^{-1} (750 m) for u and v, respectively. For v at 1500 m, there was a second large magnitude difference of –1.36 ms^{-1}.

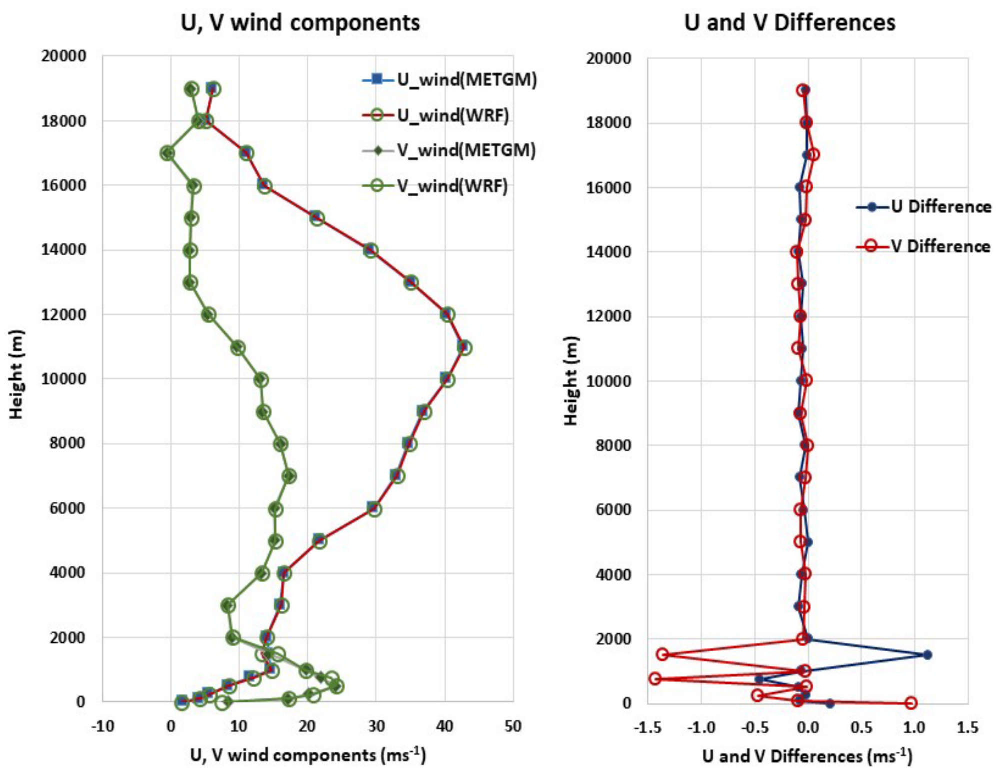


Fig. 4 Comparison of u and v wind components between METGM and WRF where the vertical coordinate of the input is height. In the scale of chart a) the curves mostly overlap. Chart b) presents the differences (METGM value – WRF value) at a different scale. At most levels, the values from both sources are close to one another (a few <0.01 ms^{-1}), but the u absolute difference (METGM value – WRF value) reaches a maximum of 1.12 ms^{-1} at 1500 m, and v maximum difference is 1.43 ms^{-1} at 750 m.

The comparisons shown in Figs. 1–4 were derived from data for WRF and METGM output with a 9-km horizontal grid interval for a location centered near TBR. Similar comparisons (not shown) using 9-km gridded output for a domain centered not far from Sierra Vista (SV), Arizona, that contains complex terrain showed similar or smaller differences. The few relatively large differences that appeared in the TBR RH and u, v data were mostly smaller in the SV data. An example is the fairly large RH difference of 7.58% at 1500 m (TBR) versus 1.55% at the same height AGL (SV). The v difference of 1.43 ms^{-1} at 750 m for the TBR grid dropped to 1.36 ms^{-1} for the SV grid.

Although the comparisons to date are limited and do not cover a large number of distinct climate regions, they do suggest that the procedure that uses height (AGL) as the vertical coordinate can generate METGMs that reproduce profiles of MET variables from WRF output to a reasonably good accuracy.

5.2 Pressure as the Vertical Coordinate

Profiles of MET variables from METGMs that were derived from WRF output that used pressure as the vertical coordinate generally do not match profiles extracted directly from WRF as well as those for METGMs derived using height AGL as the vertical coordinate. The data for Fig. 5 were derived for the same region as for Fig. 1, but the input vertical coordinate was pressure. Figure 5 has the same units and format as Fig. 1.

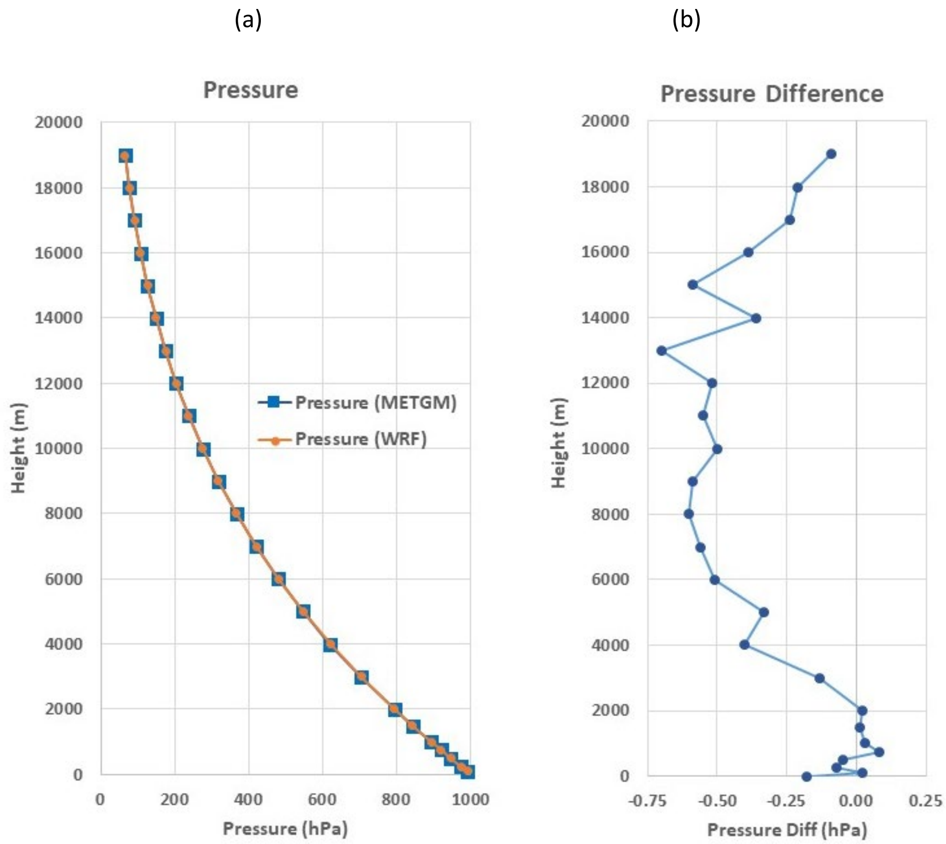


Fig. 5 Comparison of pressure (hPa) between METGM and WRF where the vertical coordinate of the input is pressure. In the scale of chart a) the curves seem to overlap. Chart b) presents the differences (METGM value – WRF value) at a different scale. The differences are near 0 up through 2000 m, but are near –0.5 hPa from about 4000 through 16000 m. The absolute values of the differences at most levels exceed those when height is the vertical coordinate (Fig. 1).

The differences for the other variables were mostly larger as well. Figure 6 presents comparisons of the u and v wind components as in Fig. 4, but where the input had pressure as the vertical coordinate. The differences for several levels were noticeably larger, especially nearer the surface. However, the difference for any one level may be smaller for the pressure-based data.

(a) (b)

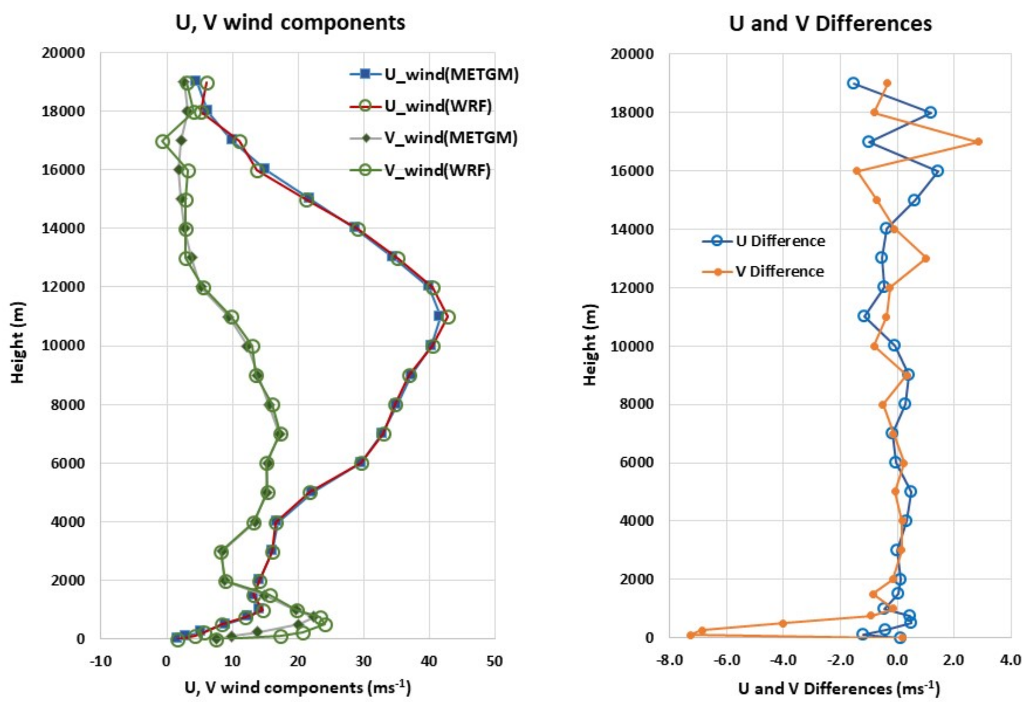


Fig. 6 Comparison of u and v wind components between METGM and WRF where the input vertical coordinate is pressure vs. height as in Fig. 4. In the scale of chart a) the curves seem to mostly overlap. Chart b) presents the differences (METGM value – WRF value) at a different scale. At most levels, the values from both sources were not as close to one another as in Fig. 4. The u absolute differences (METGM value – WRF value) reached a value of 1.18 ms^{-1} at 100 m and even larger at 16000 and 19000 m (1.42 and 1.52 ms^{-1}, respectively). Near the surface the maximum v differences were much larger, 7.29, 6.87, and 4.01 ms^{-1} at 100, 250, and 500 m, respectively).

One possible cause of the mostly larger differences may be the use in the FORTRAN program, metascii2metgm, of the mean vertical profile of height AGL calculated from the available pressure and height data. Although WRF output normally includes pressure at the model terrain surface, it is not used in the FORTRAN program. The direct use of the surface pressure from WRF output will be addressed in a future version. This procedure should lead to reasonable results if the terrain does not vary significantly over the WRF subdomain. As an initial check, the program was run for the same region, but a smaller subdomain was extracted that excluded some of the more complex terrain. The outcome appears to support this hypothesis. Figures 7 and 8 are similar to Figs. 5 and 6, but were computed using a smaller subdomain (13 × 13 vs. 85 × 75 grid points). The pressure differences were smaller at most heights, but the u and v differences were noticeably smaller only at the lowest heights. The scale of Fig. 8b presenting the pressure differences was kept the same as Fig. 6b so as to show the differences more clearly.

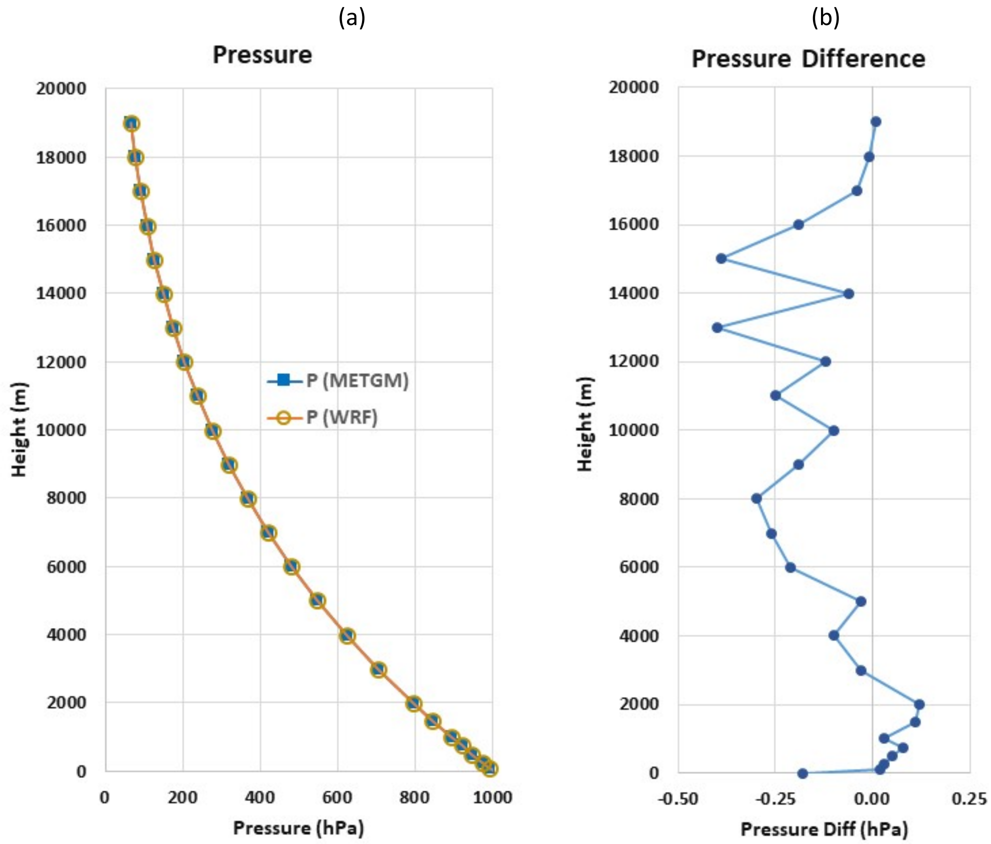


Fig. 7 Comparison of pressure (hPa) between METGM and WRF from a smaller WRF subdomain where the vertical coordinate of the input is pressure. In the scale of chart a), the curves seem to overlap. Chart b) presents the differences (METGM value – WRF value) at a different scale. The differences are not far from 0 up through 5000 m, but are near –0.4 hPa at 13000 and 15000 m. The absolute values of the differences at many heights are similar to those when height is the vertical coordinate (Fig. 1).

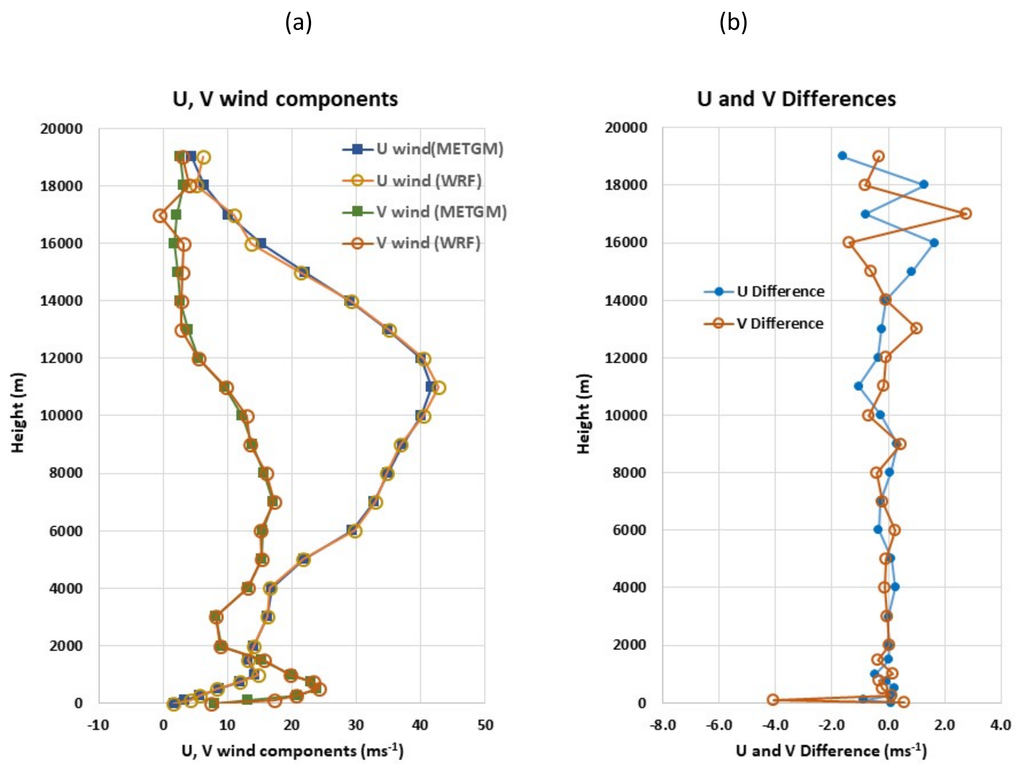


Fig. 8 Comparison of u and v wind components between METGM and WRF from a smaller WRF subdomain where the vertical coordinate of the input is pressure. In the scale of chart a), the curves seem to overlap at many heights. Chart b) presents the differences (METGM value – WRF value) at a different scale. At most levels, the values from both sources are fairly close to one another. Nevertheless, the u absolute difference (METGM value – WRF value) reached a maximum of 1.62 ms^{-1} at 16000 and 19000 m, greater than in Fig. 6. The maximum absolute v differences were still large (4.09 ms^{-1} at 100 m and 2.75 ms^{-1} at 17000 m), but not as much as in Fig. 6.

Another potential cause of greater differences between a profile from a METGM and the respective one directly from WRF output when using pressure coordinate input is the computation of pressure at the model domain surface (terrain elevation). For the METGM surface, pressure is calculated from the sea-level pressure, terrain elevation, and surface temperature and humidity. Values of temperature and humidity at sea level are not available and extrapolation may lead to a greater difference in surface pressure. Over low terrain heights, the METGM's pressure profile should be fairly close to the model's pressure profile, but for high terrain, the difference between them may be relatively large. Differences with respect to the other variables may occur, but may not be as pronounced. The combination of the use of a mean METGM height profile along with the computation of surface pressure may lead to noticeable differences over complex terrain at higher elevations. Figures 9 and 10 show the pressure and u, v wind component profiles, respectively, similar to those in Figs. 1 and 4. The WRF subdomain and smaller area of the computed METGM were centered a short distance to the west of SV.

The WRF output had a forecast date and time of 21 January 2019 at 1800 UTC and the horizontal grid resolution was 1 km. The center of the METGM was at 31.5002°N and 110.6507°W (–110.6507°), which coincides with a grid point in the WRF subdomain to the nearest 0.0001°. Model subdomain terrain heights varied from less than 1200 to over 2500 m MSL. The center point of the METGM had an elevation of 1538.6 m.

(a) (b)

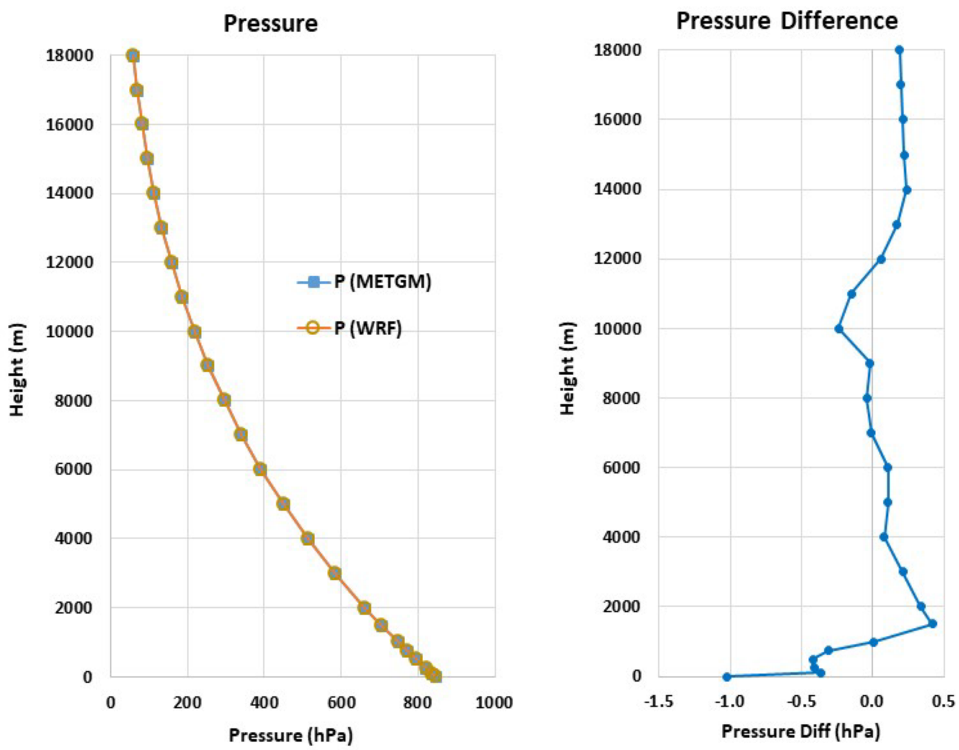


Fig. 9 Comparison of pressure (hPa) between METGM and WRF where the vertical coordinate of the input is pressure and the horizontal grid resolution is 1 km. The WRF subdomain covered an area centered to the west of SV, with a center near that of the METGM; the METGM was centered at 31.5002°N and 110.6507°W. The model terrain height for the profiles of this figure was 1538.6 m MSL. In the scale of chart a), the curves seem to overlap. Chart b) presents the differences (METGM value – WRF value) at a different scale.

(a) (b)

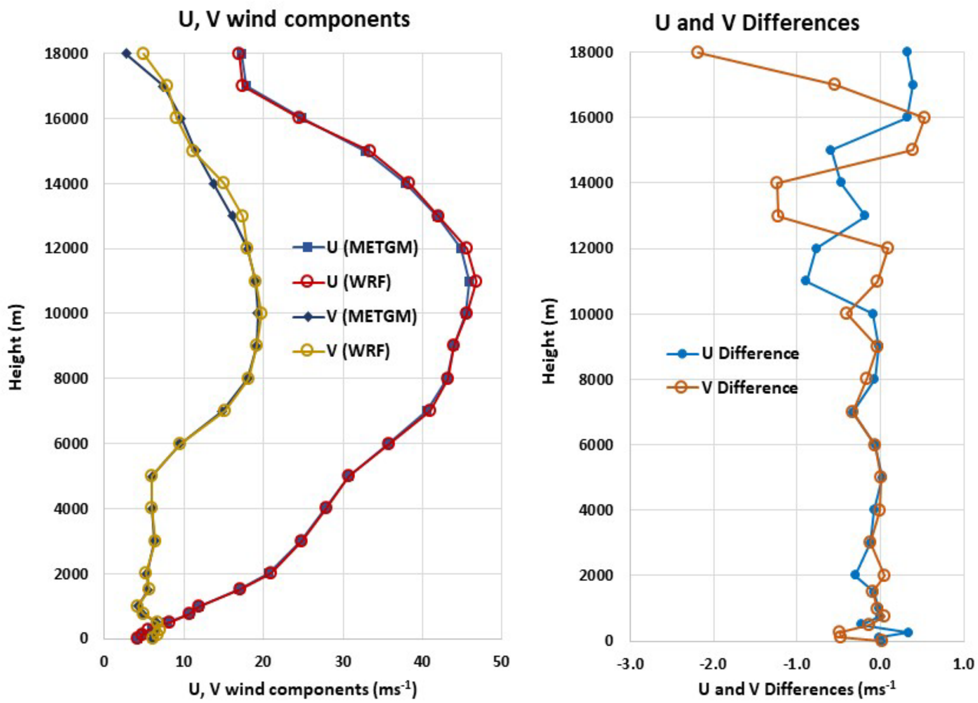
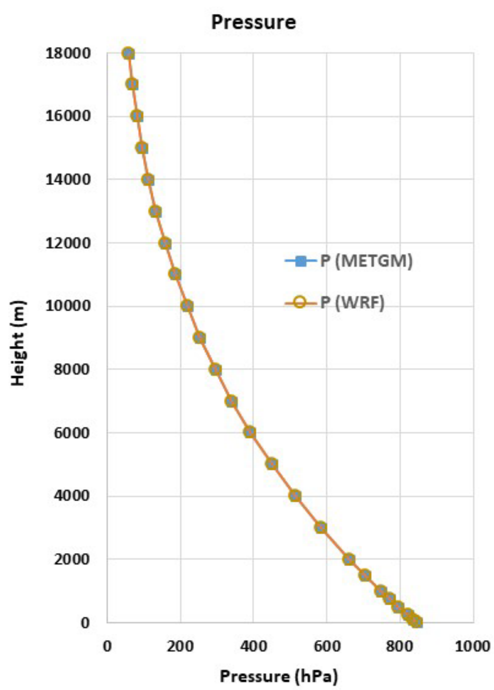


Fig. 10 Comparison of u and v wind components between METGM and WRF where the vertical coordinate of the input is pressure and the horizontal grid resolution is 1 km. The location of the WRF subdomain and centers of the WRF and METGM are the same as in Fig. 9. In the scale of chart a), the curves nearly overlap at many heights. Chart b) presents the differences (METGM value – WRF value) at a different scale. Note that the scale of b) is smaller than Figs. 6b and 8b.

The profiles of pressure from METGM and directly from WRF nearly overlap at the scale of Fig. 9a. However, as seen in Fig. 9b, the differences are somewhat larger, especially at the surface. The differences in the horizontal wind components are noticeable at several heights, but at the scale of Fig. 10a they appear to overlap at many heights. The differences at many levels are not as large as in Figs. 6b and 8b; the smaller scale of the horizontal axis in Fig. 10b should be taken into account.

Figures 11 and 12 present profiles for the same location where height is the vertical coordinate. The profiles of pressure in Fig. 11a overlap at the scale of the chart, and the differences in pressure of Fig. 11b are smaller than in Fig. 9b at most heights. In Fig. 10a (pressure vertical coordinate) and Fig. 12a (height vertical coordinate), the u and v values appear nearly the same at the scale of those charts. However, for all but a few heights, the magnitude of the difference in u and v were smaller for the data with height as the vertical coordinate, as can be seen by comparing Fig. 10b with Fig. 12b, especially for heights greater than or equal to 2000 m. On average, the values of the absolute differences in u and v were greater for the data using pressure as the vertical coordinate by 0.39 ms^{-1} (u) and 0.44 ms^{-1} (v), respectively.

(a) (b)



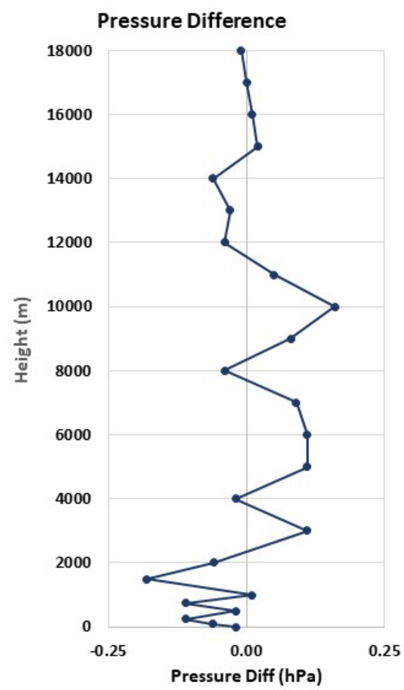


Fig. 11 Comparison of pressure (hPa) between METGM and WRF as in Fig. 9, but where the vertical coordinate of the input is height

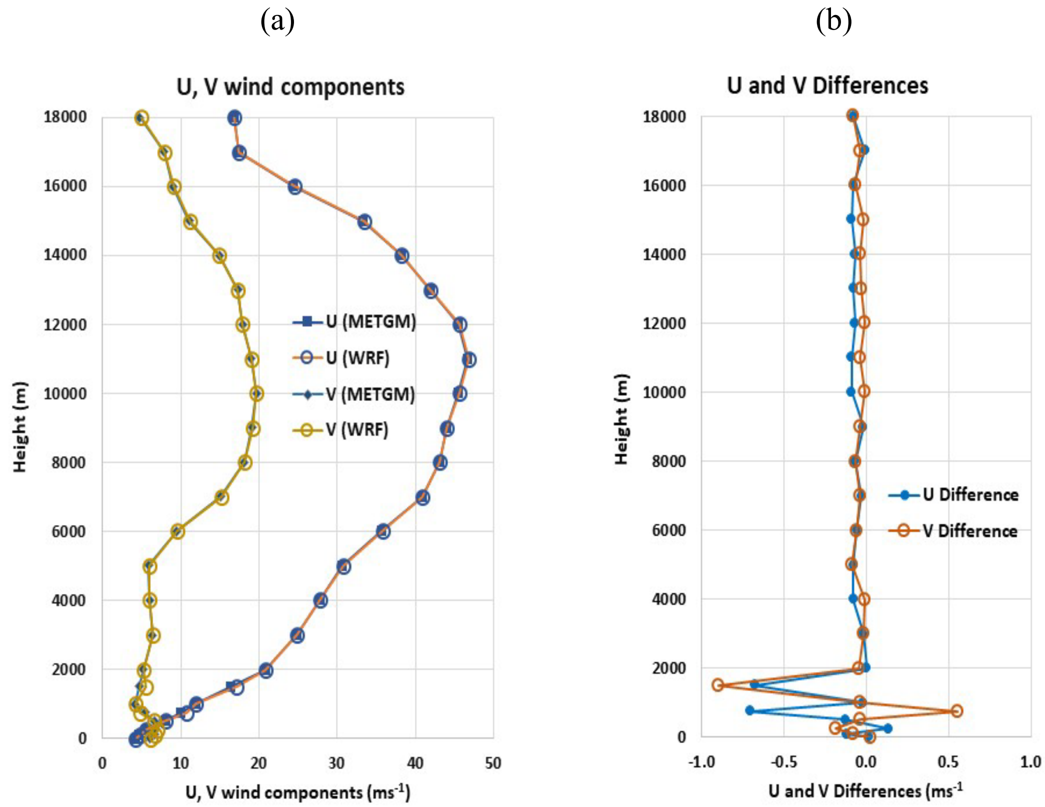


Fig. 12 Comparison of u and v wind components between METGM and WRF as in Fig. 10, but where the vertical coordinate of the input is height.

Figures 13 and 14 present profiles of the difference in temperature and RH between a METGM profile and one extracted directly from WRF for the same location near SV at a horizontal resolution of 3km, where one line shows the differences when the vertical coordinate is height AGL and the other when the vertical coordinate is pressure. In Fig. 13, the differences for the pressure coordinate are much larger below 1000 m (except for the surface) and from 11000 to 14000 m. In Fig. 14, the magnitude of the differences are greater for the data with pressure as the vertical coordinate at most heights, and especially larger at 14000, 7000, and below 1000 m, except at the surface. At 1500 m, the absolute value for the data with height AGL as the vertical coordinate is notably larger.

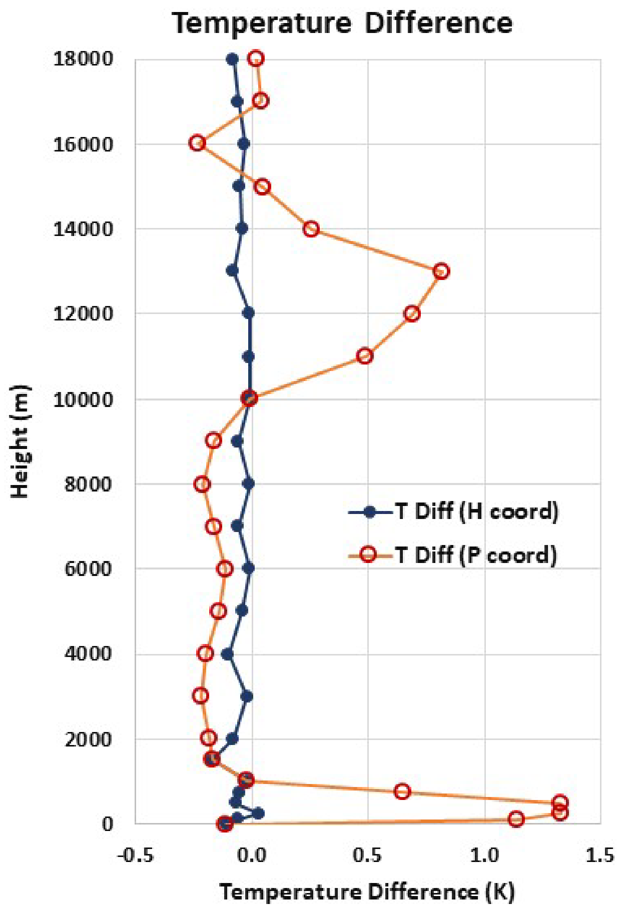


Fig. 13 Comparison of temperature (K) between METGM and WRF profiles for the same location near SV where the blue line is for data having height (m AGL) as the vertical coordinate and the orange line is for data having pressure (hPa) as the vertical coordinate. The horizontal grid resolution was 3 km.

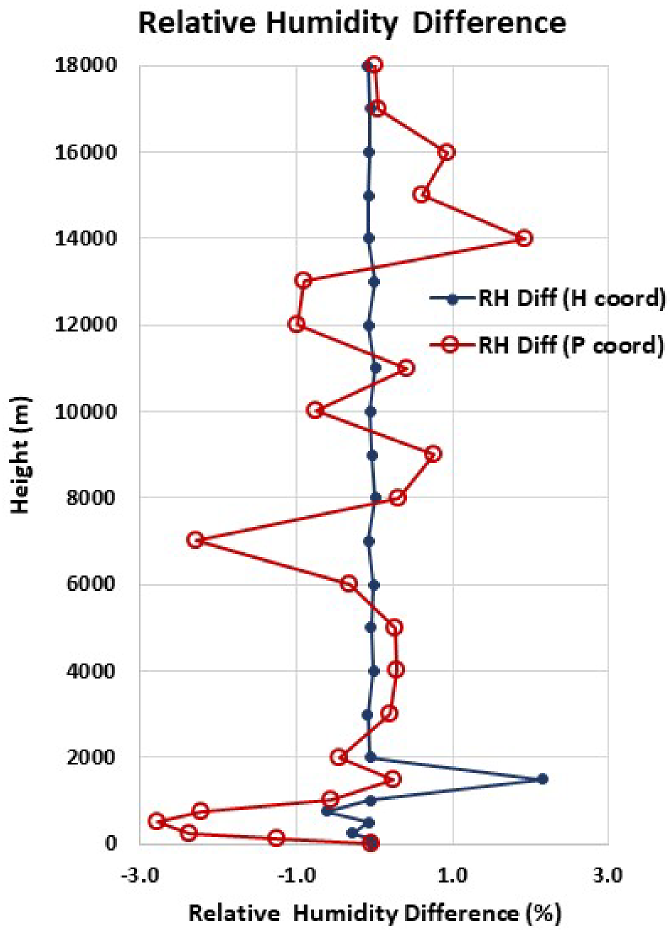


Fig. 14 Comparison of RH (%) between METGM and WRF profiles for the same location near SV where the blue line is for data having height (m AGL) as the vertical coordinate and the orange line is for data having pressure (hPa) as the vertical coordinate. The horizontal grid resolution was 3km.

Another way to examine the data with the different vertical coordinates is to compare the number of data levels (METGM heights) where the absolute value of the difference is less than some value. Table 12 presents the number of data levels where the absolute value of the difference is less than a specified value for all the variables examined. The WRF subdomain, and date and time, were the same as used for Figs. 9–14. As shown in Table 12, the differences using the height vertical coordinate are generally smaller and have fewer large differences.

Table 12. Number of METGM height levels for the data with height or pressure as the vertical coordinate where the absolute difference in a variable is less than the respective specified value as listed in the table. The specified values are for pressure (P in hPa), temperature (T in K), RH (in %), u wind component (U in ms^{-1}), and v wind component (V in ms^{-1}). H vert coord and P vert coord indicate the data with height and pressure as the vertical coordinate, respectively.

	Variable				
	P	T	RH	U	V
Criterion	< 0.5	< 0.5	<1.0	<0.5	<0.5
H vert coord	24	24	23	22	22
P vert coord	23	16	16	18	15
Criterion	<0.1	<0.1	<0.1	<0.1	<0.1
H vert coord	17	23	21	19	21
P vert coord	6	11	4	7	5

6. Conclusion

This report presents a method to obtain a METGM from WRF output. A Bash script that calls an NCL script and then a Python 3 script produces a text version of a WRF output file. The text file in turn is input to a FORTRAN program originally developed by Weber (2002a) that was modified here for the work of this report. The software may be run via a single Bash script that combines the several scripts and a FORTRAN program. The limited comparisons presented in this report suggest that the version of the software that uses height AGL as the vertical coordinate produces METGMs that contain vertical profiles of the several variables that are close to those extracted directly from the respective WRF output. The version using pressure as the vertical coordinate generates METGM-derived vertical profiles that are not as close to the profiles from the respective WRF output. Additional work is planned for an upgrade that may improve the output when pressure is the vertical coordinate. Nevertheless, both versions produce files that verify as valid METGMs based on results from a standard software tool developed elsewhere for NATO application.

Given the relative abilities of the two versions of the program to reproduce profiles from the WRF output, use of the version using height as the vertical coordinate is recommended whenever possible. If output from other models can only be converted to text with pressure as the vertical coordinate, then the version of the software the uses pressure as the vertical coordinate may be used as a backup. For terrain that is not complex and is relatively close to sea level, both versions should produce comparable results.

The current package of code is not proposed as an operational set of software, but can be used in experimentation and evaluation, and to test other methods that produce a METGM or applications that may employ a METGM as input. The METGM's primary application is to provide MET information for use in fire control systems, but may be used for other purposes such as for transport and diffusion of smoke or other obscurants.

7. References

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Cogan J. Evaluation of model-generated vertical profiles of meteorological variables: method and initial results. Meteorol Appl. 2017;24:219–229.

Reen B. Army Research Laboratory (US), Adelphi Laboratory Center, MD. Personal communication, 2017.

STANAG 4082 MET – edition 3. Adoption of a standard artillery computer meteorological message. Brussels (Belgium): Military Agency for Standardization, NATO; 2012.

STANAG 6022 MET – edition 2. Adoption of a standard gridded data meteorological message. Brussels (Belgium): Military Agency for Standardization, NATO; 2010.

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Weber H. Schule ABC-Abwehr und Gesetzliche Schutzaufgaben, BerWiss, Dez GeoInfo, Private communication. 2002b.

8. Additional Resources

Various web sites have links to information on artillery systems around the world. Examples include the following:

- http://www.military-today.com/artillery.htm,
- https://www.army-technology.com/features/featurethe-10-most-effective-self-propelled-artillery-4180888/, and
- http://www.deagel.com/Artillery-Systems.htm.

The Army-technology site has further information on some specific systems: https://www.army-technology.com/projects/2s35-koalitsiya-sv-152mm-self-propelled-howitzer/.

The following National Center for Atmospheric Research (NCAR) and University Corporation for Atmospheric Research (UCAR) website and the included links have information on WRF:

- https://www.mmm.ucar.edu/weather-research-and-forecasting-model

Appendix A. High-level Flowcharts

This appendix contains higher-level flowcharts (Figs. A-1 through A-6) for six of the scripts and programs of this report. The flowchart for the Bash script wrf2metgm.sh mostly shows the differences from wrf2text.sh. It does not query the user for the name of the text file to be used as input to metascii2metgm and adds a query on whether or not the user wants to directly view the output to screen.

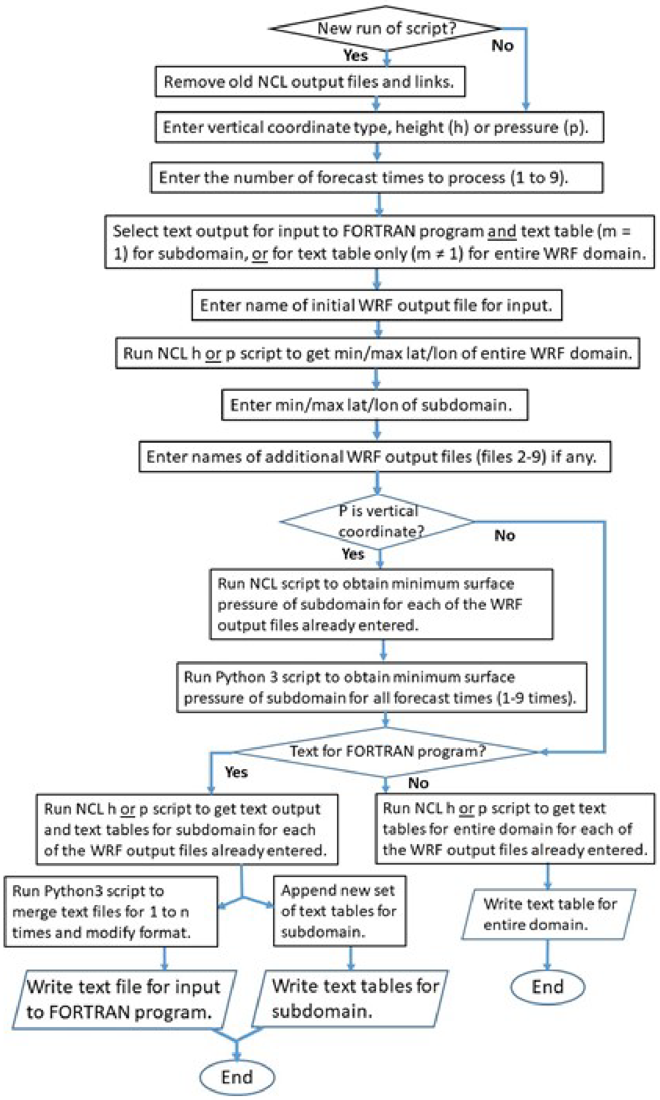

Fig. A-1 Flowchart of wrf2text.sh

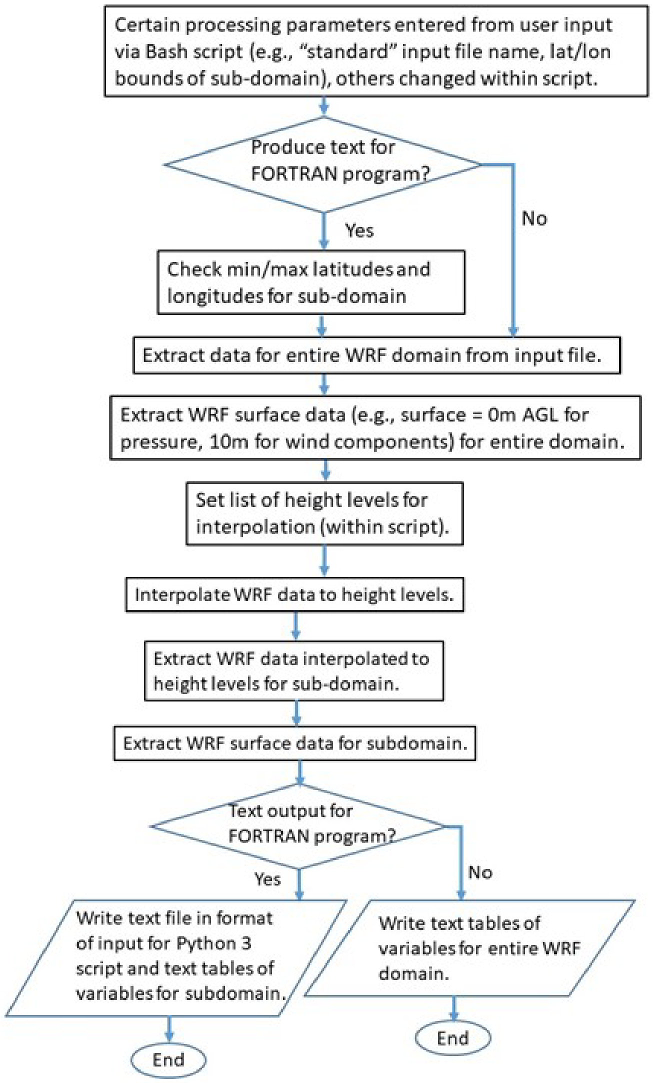

Fig. A-2 Flowchart of wrf2textgmh.ncl. Details in text. For wrf2textgmp.ncl, the interpolation of WRF data to height (geopotential) levels is replaced by interpolation to pressure levels.

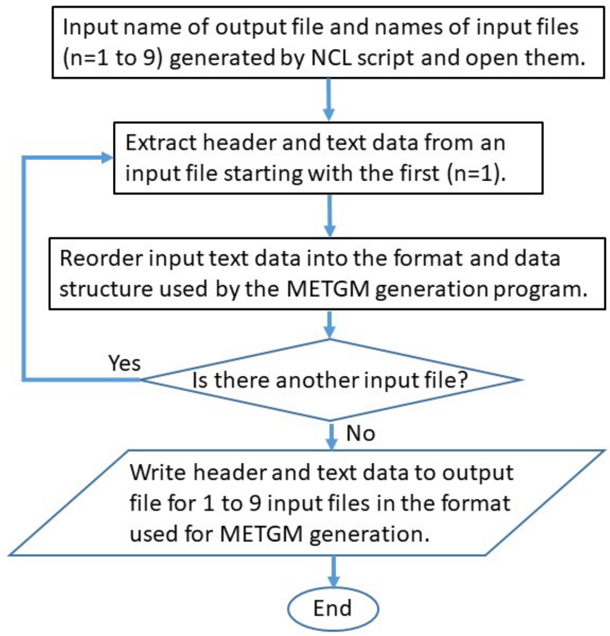

Fig. A-3 Flowchart for wrftexth.py. The flowchart for wrftextp.py is the same though the script itself differs from wrftesth.py in some details.

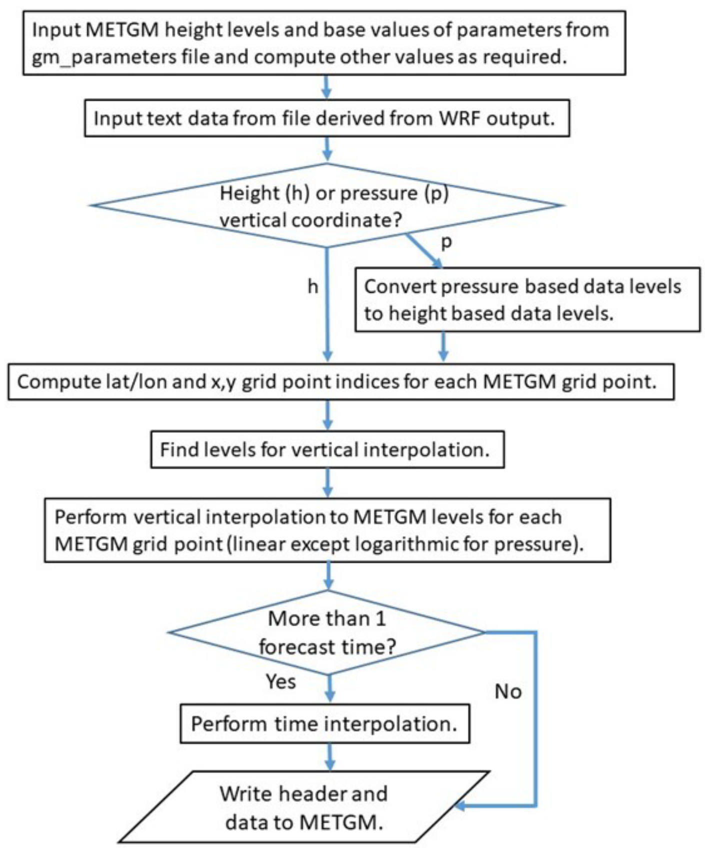

Fig. A-4 Flowchart for metascii2metgm.f. Use of height as the vertical coordinate is recommended as the preferred option.

n.f

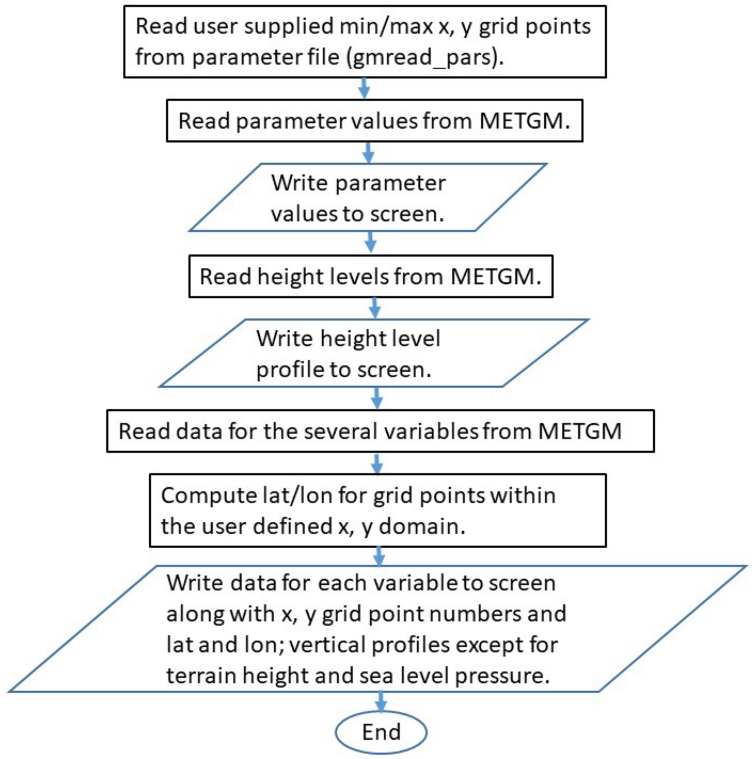

Fig. A-5 Flowchart for readmetgm.f

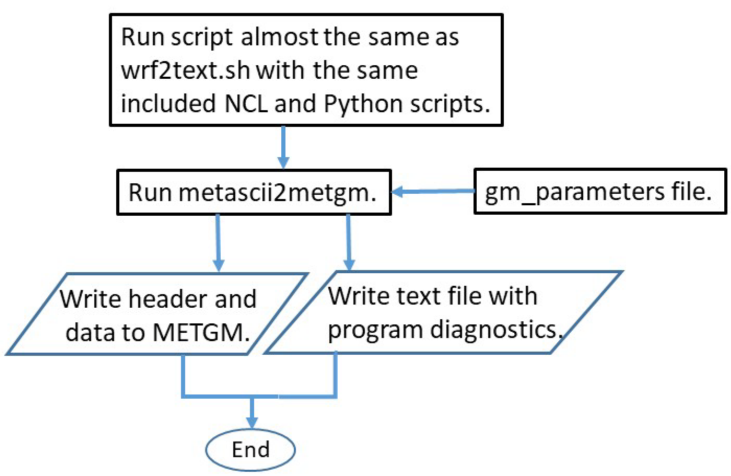

Fig. A-6 Flowchart showing main parts of wrf2metgm.sh. For the script mentioned in the first box, the option for text table output for the entire domain available in wrf2text.sh was removed since it is not needed. Otherwise that script is the same as wrf2text.sh.

Appendix B. Source Code for Selected Scripts

Appendix B contains the source code listings as attached files in the PDF attachment pane for wrf2text.sh, wrf2textgmh.ncl, and wrftexth.py. They are in text file format and end with the extension ".txt" (e.g., wrf2textgmh.ncl.txt). The versions of the NCAR Command Language (NCL) and Python 3 scripts for pressure (wrf2textgmp.ncl and wrftextp.py) are nearly the same except for several lines of code concerning the choice of the vertical coordinate. A sample of the parameter file (gm_parameters) for the metascii2metgm program is included in this appendix as Table B1.

The Bash script wrf2text.sh is attached as (wrf2text.sh.txt). It requests information from the user that guides the script as to what actions to undertake and as to what input to provide to the called NCL and Python 3 scripts. It acts as an overall main script to generate text versions of Weather Research and Forecasting (WRF) output files that become the input to the FORTRAN program (metascii2metgm) that generates a gridded meteorological message (METGM). More details are discussed in the main text of this report.

The NCL script converts a WRF output file into text output for one forecast time for a domain specified by user supplied minimum and maximum longitudes and latitudes. The version presented here, wrf2textgmh.ncl, has geopotential height (above ground level [AGL]) as the vertical coordinate. It extracts data for the required variables from the entire domain, generates a subdomain, and reorders the data in the subdomain onto geopotential height levels. The version that uses pressure as the vertical coordinate is the same except for several lines of code directly related to the type of vertical coordinate. Details and sample output appears in the main text of this report.

The Python 3 script consolidates text output from the NCL script into a single text file for one to three forecast times, modifies the header, and reorders the output from lists of values for each height over the entire subdomain to values from the surface to the highest level (vertical profile) for each grid point in the subdomain. The version presented here, wrftexth.py, has geopotential height (AGL) as the vertical coordinate. The version that uses pressure as the vertical coordinate is the same except for various lines of code directly related to the type of vertical coordinate. Details and sample output appears in the main text of this report.

The FORTRAN program metascii2metgm was modified to allow input of many of the parameters via a text file, gm_parameters, instead of hard coding via data statements and fixed definitions. Consequently, operation of the program is more user friendly now that most changes to the operating parameters do not require recompilation. It also means a smaller chance of making unintended changes to other parts of the program when modifying one or more parameters. Other changes included replacement of the subroutine for computation of heights AGL that is employed when the input file has pressure as the vertical coordinate. Issues with some parts of the interpolation code were resolved. Additional information on gm_parameters and the program metascii2metgm.f may be found in the main text of this report. Table B-1 shows an example gm_parameters file. The FORTRAN program readmetgm was modified to allow input of minimum and maximum x and y METGM grid points via a text file, gmread_pars. Previously data for only 1 grid point, with the x and y position hard coded within the program, was written to the screen.

Table B-1 Example of a gm_parameters text file for use with the metascii2metgm FORTRAN program. The first line has the first part of the output (METGM) file name. The name shown indicates the METGM is for part of southeast Arizona. The rest of the output file name has the date and time normally followed by the suffix ".gm". The second line tells the program to extract a small 3 × 3 horizontal (x, y) grid from the input WRF text file. The third line has the grid interval in terms of longitude and latitude followed by the time interval in seconds (it must be listed even if using only one time). The longitude and latitude intervals shown closely approximate those for the 9-km WRF domain of this sample with a center latitude as listed in the fourth line, which contains the center point in longitude and latitude. The remaining lines have the vertical heights (m AGL) of the output METGM grid.

```
SouthEastAZ
3 3
0.095164  0.081081  3600.
-110.6823  31.5091
0
100
250
500
750
1000
1500
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000
13000
14000
15000
16000
17000
18000
19000
```

Table B-2 Sample gmread_pars file for use with readmetgm. The values listed are the minimum and maximum x and y grid point numbers respectively. In this sample the program will write values for 4 grid points. Output for 1 grid point still requires four numbers. For example, replace 3 in both lines with 2 to write values for grid point x = 2, y = 2 only.

```
2  3
2  3
```

List of Symbols, Abbreviations, and Acronyms

AGL	above ground level
MET	meteorological
METGM	gridded meteorological message
NATO	North Atlantic Treaty Organization
NCAR	National Center for Atmospheric Research
NCL	NCAR Command Language
NetCDF	Network Common Data Form
NWP	numerical weather prediction
UCAR	University Corporation for Atmospheric Research
WRF	Weather Research and Forecasting model

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FCDD RLC E
J COGAN