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# High-Resolution Gridded Observations System for Numerical Weather Prediction Model Assessment, Version 1.0

by John W Raby and Jeffrey A Smith

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# High-Resolution Gridded Observations System for Numerical Weather Prediction Model Assessment, Version 1.0

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<p>The High-Resolution Gridded Observations System generates high-resolution gridded observations using the MetPy <code>interpolate_to_grid</code> Python tool. Gridded observations are used as ground truth for evaluating high-resolution Numerical Weather Prediction model forecasts in a spatial framework that enables assessment of the true value of high-resolution forecasts. The tool, as received from MetPy, uses five different interpolation techniques that take meteorological observations from irregularly spaced point locations and produces a uniform grid that contains the interpolated values of the observations. The gridded observations are then plotted on a map. The tool was modified to generate observations on grids with sub-kilometer grid spacing. In addition, the tool was modified (1) to read an input text file different from the default text file and (2) to output the gridded observations using a different map projection and array type to ensure compatibility with model assessment software. The tool, which is run in a Python script, can be edited to specify which interpolation technique(s) will be used as well as various parameters that control the interpolation. The output gridded observations are plotted on the original map and can be passed to the Model Evaluation Tools (MET) and METplus Wrappers, which compute numerous spatial skill scores and error statistics for input model forecasts.</p>					
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## 1. Introduction

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The High-Resolution Gridded Observations System generates high-resolution gridded observations using the MetPy `interpolate_to_grid` Python tool (May et al. 2022). Gridded observations are used as ground truth for evaluating high-resolution Numerical Weather Prediction (NWP) model forecasts in a spatial framework, which enables better assessment of the true value of high-resolution forecasts as opposed to the more traditional grid-to-point methods that use only point observations (Ebert 2008). The tool, as received from MetPy, is the core software component and uses five different interpolation techniques that take meteorological observations from irregularly spaced point locations and produces a uniform grid that contains the interpolated values of the observations (McNulty 2011). The gridded observations are then plotted on a map background. The tool was modified to reduce the grid spacing of the output gridded observations from 75 km to less than 1 km. In addition, the tool was modified (1) to read an input text file formatted differently from the default text file, (2) to output the gridded observations in a NetCDF file, and (3) to use a different map projection and array type to ensure compatibility with model assessment software and forecast output. The tool that is run in a Python script can be edited to specify which interpolation technique(s) will be used, the various parameters that control the interpolation, the name and location of the input point observations file, and other aspects of the tool. The output gridded observations are plotted on the default map background and can be passed as an array in memory to the Model Evaluation Tools (MET) and METplus Wrappers (hereafter METplus Wrappers is simply referred to as METplus for brevity), which compute numerous spatial skill scores and error statistics for input model forecasts (Prestopnik et al. 2022; Opatz et al. 2023).

The High-Resolution Gridded Observations System was developed to fulfill the need for gridded observations, often referred to as analyses, to enable the use of spatial verification techniques for verifying high-resolution NWP forecasts. Jolliffe and Stephenson (2012) describe a number of such techniques. Sources of gridded observations are few, particularly at the sub-kilometer spatial scale needed for high-resolution NWP forecasts in complex terrain conditions. In particular, forecasts produced by the Weather Research and Forecasting (WRF)-Advanced Research WRF (ARW) when run using the Large Eddy Simulation (LES) option fall into this category of high-resolution NWP (Skamarock and Klemp 2008) (hereafter WRF-ARW with the LES option is simply referred to as WRF-LES for brevity). In the continental United States (CONUS), the only available source of gridded observations is the UnRestricted Mesoscale Analysis (URMA) (De Pondeca et al. 2011). The URMA is produced by the National Oceanic and Atmospheric Agency

(NOAA) National Weather Service (NWS). The URMA is also used by the NWS for verifying NWP models. However, the native resolution of URMA is 2.5 km, which is insufficient for verifying WRF-LES simulations. Another source of gridded observations is the model analysis, which is used to initialize the forecast phase of the simulation. However, use of the model analysis is not considered a fair approach for verification of the forecasts from the same model (Jolliffe and Stephenson 2012).

## **2. System Description**

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### **2.1 Original System**

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The core component of the High-Resolution Gridded Observations System is the MetPy `interpolate_to_grid` Python tool, which is the script-driven software that generates gridded observations using five different interpolation techniques. The original tool initializes the computing environment by importing the needed libraries and modules as follows:

- cartopy for geospatial information (Cartopy 2021)
- matplotlib for visualizations and plotting (Hunter 2007)
- numpy for scientific computing (Harris et al. 2020)
- metpy for meteorological computing and visualizations (May et al. 2022)

The original tool then proceeds with the following steps to prepare for execution:

- Define the default map background for plotting.
- Define the input point observations data.
- Set the map projection for the plot and for the output array.
- Define the range of the meteorological variable for the input point observations.
- Assign needed variables.
- Run interpolation technique modules using the default parameter settings.
- Generate plots on default map background. The plots show the temperature over North America.

## 2.2 Modified System

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The steps required for executing the modified tool are the same as those of the original tool, with the following exceptions needed to accomplish the desired changes in grid spacing: 1) to read a formatted input text file in a different manner, 2) to output observations in a NetCDF file, and 3) to use a different map projection and array type. We implemented these as follows:

- Imported netCDF4 to interface with the NetCDF-C library (Unidata 2021).
- Defined the default map background for plotting. Reduced the extents of the default North American map background to the smaller domain corresponding to the domain of the point observations used as input.
- Defined the input point observations data. Modified the method for reading the text file to use the Python “open” command instead of the “numpy.loadtxt” function. Defined the structure of the text file data from that of the default input file to the point observations chosen for the project.
- Set the map projection for the plot and for the output array. Changed the projection from Albers Equal Area Conic to Lambert Conformal Conic and modified the central latitude and central longitude to correspond to the location of the WRF-LES domain.
- Defined the range of the meteorological variable in the input point observations. Modified the range to correspond with the range of the input point observations over the WRF-LES domain.
- Assigned needed variables. Focused the modifications on the Cressman and Barnes interpolation techniques. A new variable was needed to create an ndarray from the default masked array. The ndarray was needed to facilitate the ingest of the gridded observations into MET and METplus. A new variable was created to rename the ndarray to the name expected by MET and METplus. Temporary diagnostic variables were added for testing purposes.
- Ran the interpolation technique modules using modified parameter settings. Modified the horizontal resolution parameter to change the grid spacing from 75 km to 500 m. The MetPy documentation incorrectly defined the relationship between the value of the parameter and the actual grid spacing. This resulted in an error of 1,000 m, which was discovered during testing. Notified the MetPy maintainers who acknowledged the error and entered a fix request in the software repository on GitHub (Unidata/MetPy 2023).

- Generated plots on default map background. The plots showed the gridded observations over a WRF-LES domain centered over Southern New Mexico, West Texas, and Northern Mexico.
- Additional Modifications:
  - New code was added to create and export a NetCDF file containing the gridded observations.
  - To facilitate ingest into MET and METplus, the values of the ndarray were converted from single precision to double precision.
  - A new Python dictionary was added to define time, grid, and variable attributes required by MET and METplus.
  - The order of the dimensions of the ndarray was reversed to correct a north-south orientation issue, which presented after ingest into MET and METplus.

### 3. Results and Discussion

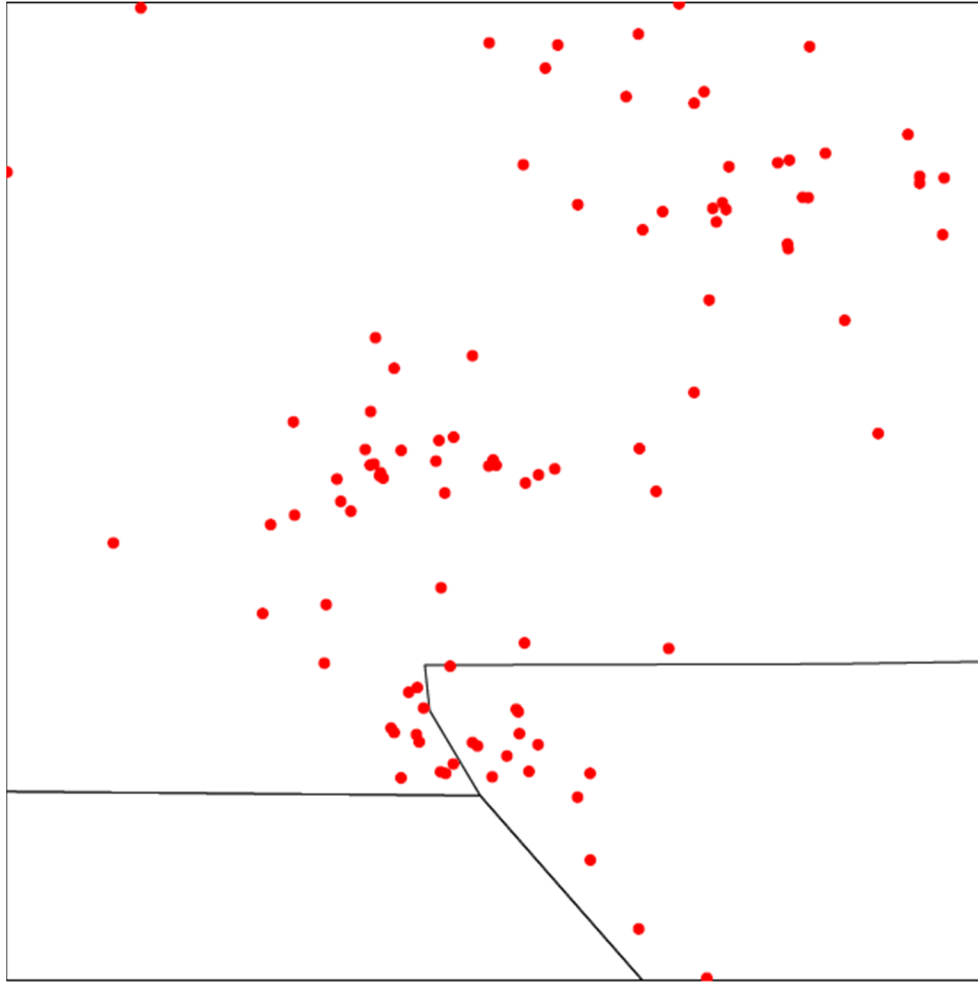
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The MetPy `interpolate_to_grid` Python tool has been tested to confirm that the gridded observations can be produced over the WRF-LES domain on a 500-m grid using the Cressman, Barnes, and Radial Basis Function interpolation techniques. Figure 1 shows an example of the input point temperature observations for the WRF-LES domain.

33.15805	-105.76889	278.14999
31.63335	-106.26485	281.483
32.32494	-106.11677	280.37201
31.8	-106.4	283.14999
32.00253	-106.853	279.81699
31.85	-106.38	279.64999
32.03	-106.09	282.85001
32.5566	-106.69997	277.64999

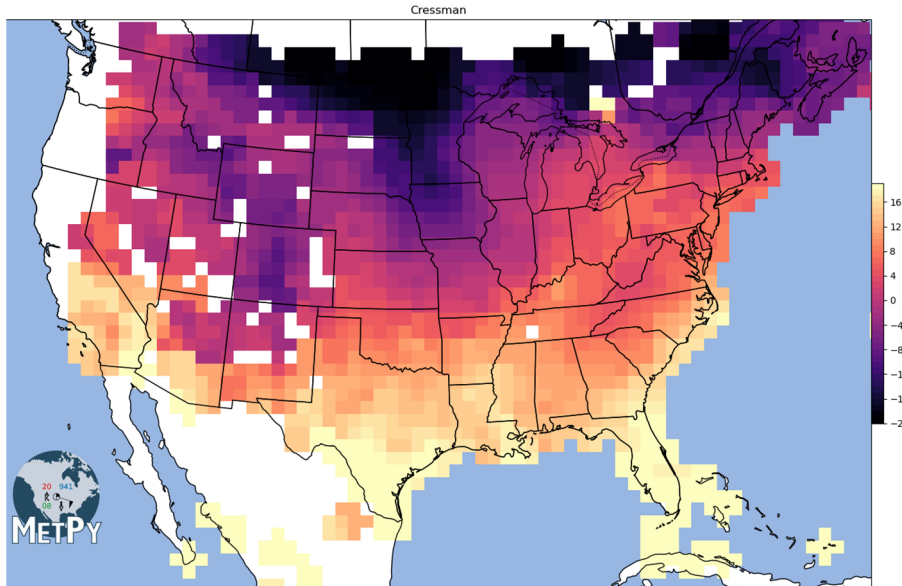
**Fig. 1** Example of 2 m above ground level (AGL) temperature point observations in column format ordered left to right for latitude, longitude, and temperature in kelvin

Figure 2 shows the WRF-LES domain with the locations of the point temperature observations.



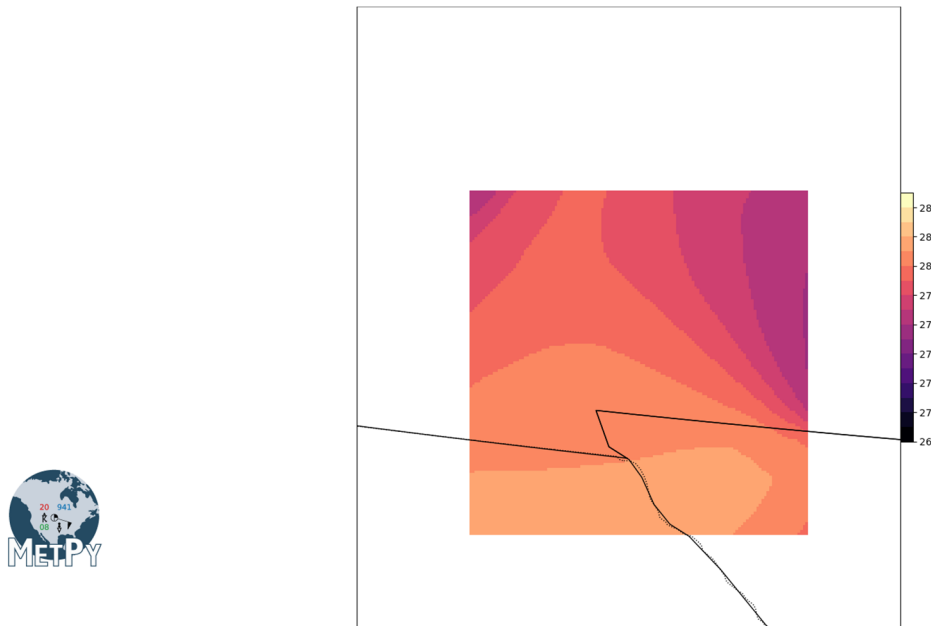
**Fig. 2** Temperature point observation locations

Figure 3 shows an example of the plot of the default gridded observations over the default North American background map using the Albers Equal Area Conic projection produced by the original MetPy `interpolate_to_grid` Python tool using the Cressman interpolation technique.

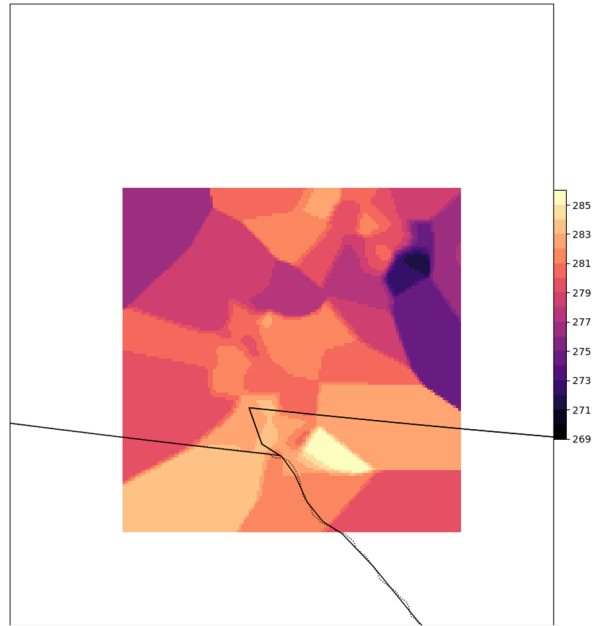


**Fig. 3** Gridded temperature observations on a 75-km grid produced by the original MetPy `interpolate_to_grid` Python tool

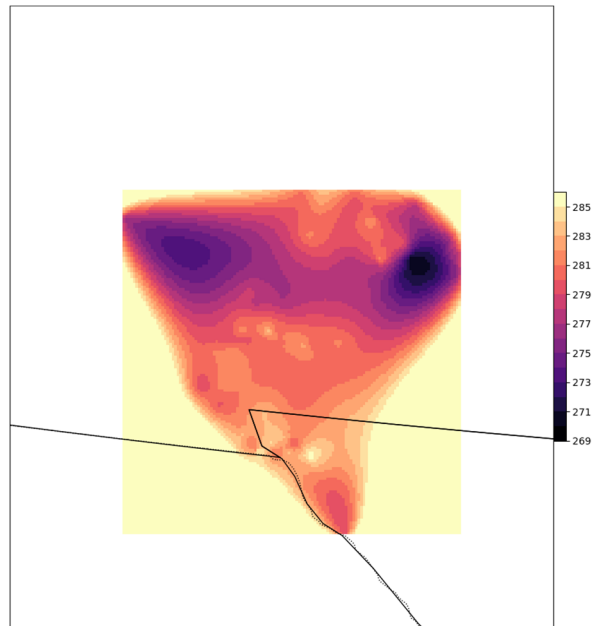
Figures 4–6 show the gridded observations produced by the modified MetPy `interpolate_to_grid` Python tool over the WRF-LES domain on the Lambert Conformal Conic projection using the Cressman, Barnes, and Radial Basis Function interpolation techniques.



**Fig. 4** Cressman gridded observations on a 500-m grid



**Fig. 5 Barnes gridded observations on a 500-m grid**

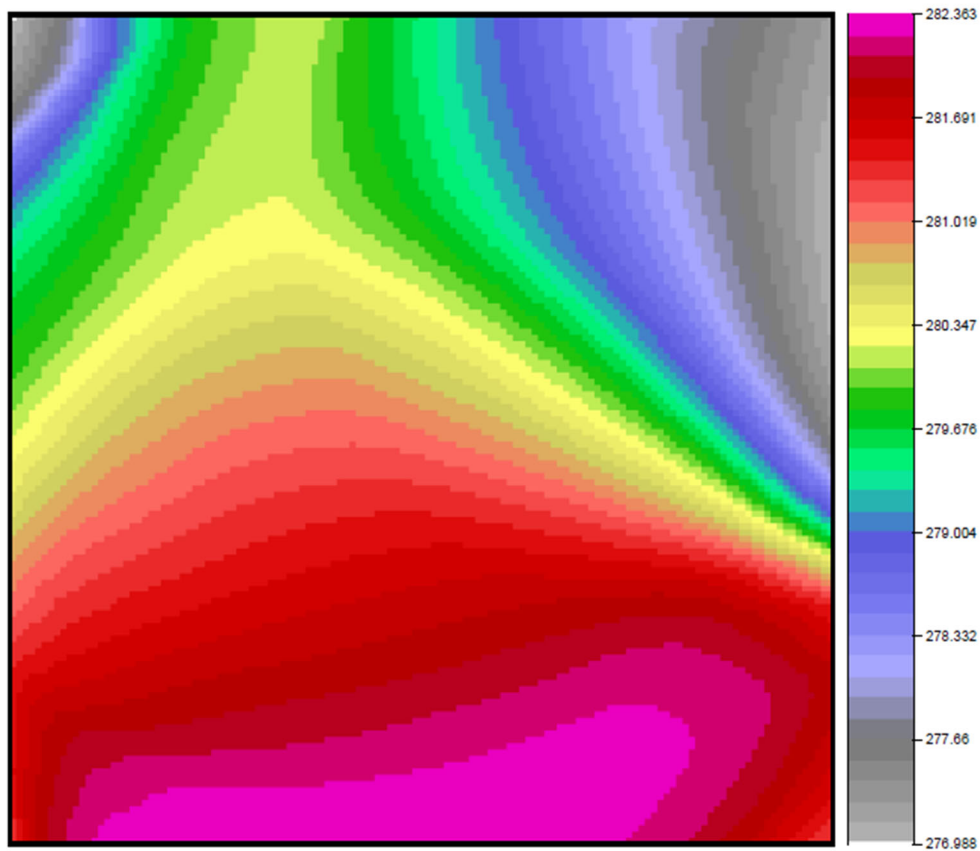


**Fig. 6 Radial Basis Function gridded observations on a 500-m grid**

After the tool was modified, testing was conducted to develop the methodology for creating a NetCDF file containing the gridded observations, which could be ingested into MET for generating the skill scores and error statistics for the NWP model forecasts. The development succeeded in producing the NetCDF file containing the gridded observations on a 2D XY grid, but the array lacked the geolocation information to enable MET to read it. A different method was tested

that involved passing the output gridded observations in memory in an ndarray to MET and METplus for processing to generate the skill scores and error statistics. The technique used for passing the ndarray, called Python Embedding, was implemented using the METplus software. Python embedding involves wrapping the Python script (MetPy interpolate\_to\_grid Python tool) using a wrapper script and specifying the name of a temporary file to be written. A system call to the Python instance results in execution of the Python script. The output data object, in this case the ndarray, is then written to a temporary NetCDF file. Python then reads the NetCDF file and provides it to the MET tool that is being executed. The workflow ends with the output from the MET tool being generated. Figure 7 shows an example of the output produced by the MET plotting tool Plot-Data-Plane.

Python enabled plot of Z2 TMP Analysis



**Fig. 7 Cressman gridded temperature observations on a 500-m grid**

Figure 8 shows an example of the output produced by the MET tool Grid-Stat, which is the difference field between the WRF-LES temperature forecast on a 1-km grid and the Cressman temperature gridded observation on a 500-m grid. Grid-

Stat was configured to regrid the forecast to a 500-m grid to achieve grid matching required for the difference and statistical computations to execute.

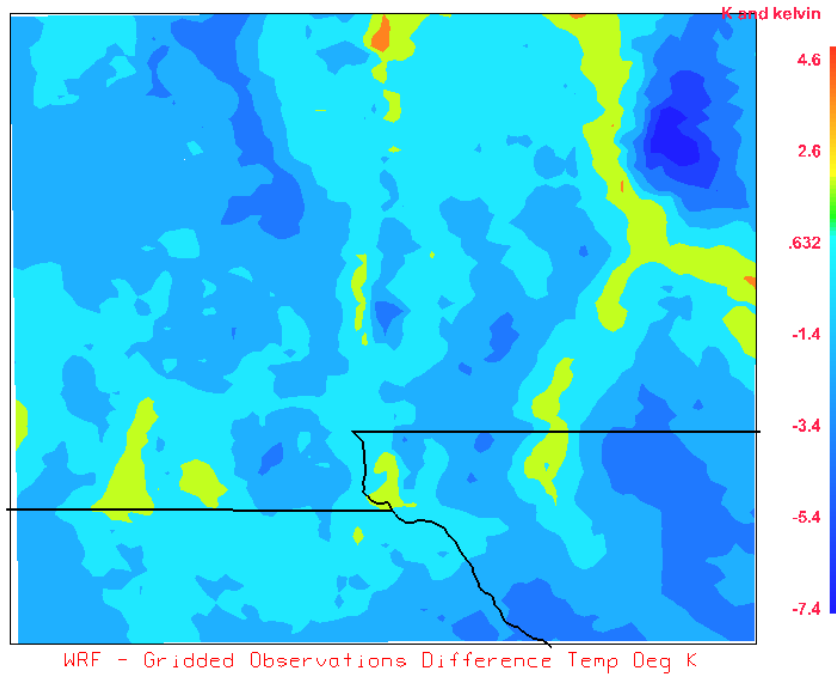


Fig. 8 Temperature difference field on a 500-m grid computed by MET Grid-Stat

#### 4. Conclusions and Future Work

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The High-Resolution Gridded Observations System is a software tool that provides the capability to generate gridded observations on sub-kilometer grids, making possible the spatial verification of high-resolution WRF-LES forecasts. The tool will enable users to ingest point observations from National Weather Service and mesoscale networks so gridded observations can be generated from them. One particularly useful source of point observations data is the matched pair output text file produced by the MET Point-Stat tool. Another possible source of point observations that is not available from the above-mentioned networks is an array of instrumented towers located in the Multipurpose Sensing Area (MSA) operated by the DEVCOM Army Research Laboratory. The MSA is in Southern New Mexico in an area of complex terrain and is included in the WRF-LES domain. The towers are configured in a regularly spaced array and are instrumented with meteorological sensors at multiple levels above the ground level.

There are several improvements that would enhance the system. First, the quality of the gridded observations needs to be evaluated. The more promising of the five interpolation methods are as follows: Barnes, Cressman, and Radial Basis Function methods, which need to be optimized by structured testing designed to evaluate the

effect of each of the parameters that control the interpolation. The testing should include comparisons with the input point observations using techniques such as cross-validation with intentional withholding of observations to evaluate the accuracy of the analysis in areas where no ground truth was assimilated into the interpolation.

Second, the utility of the system could be improved by modifying the code in the tool to accept a more versatile format of the input point observations data to facilitate the ingest of the matched pair text file from the MET Point-Stat tool and the text output files produced by parsing the tower data from the MSA. One possible alternative for this modification is the development of code that can be used to postprocess the above input data into a common, standardized format that can be ingested into the interpolation tool.

Third, another enhancement of the system is to complete the development of the capability to output a NetCDF file containing the gridded observations that is compatible with MET. The value of this enhancement is that a permanent file that preserves the gridded observations can be generated. The file is then available for ingest into MET for future model assessment studies. In addition, this would enable the running of the interpolation tool in a simpler, standalone mode rather than as a process embedded within MET and METplus.

The development of the High-Resolution Gridded Observations System is a step forward to achieving the goal of producing gridded observations needed for performing spatial verification of forecasts produced by the WRF-LES. The WRF-LES, in conjunction with MSA-point observations, is being used by ARL atmospheric scientists to observe and simulate conditions and flow patterns in the atmospheric boundary layer under varying topographical and large-scale meteorological conditions (Dumais et al. 2023). Our ability to evaluate the accuracy of the simulations is critical to ensure that the understanding gained from the simulations are valid. Enhancements are needed to improve the system so that assessments of the simulations are accurate.

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## List of Symbols, Abbreviations, and Acronyms

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AGL	above ground level
ARW	Advanced Research Weather Research and Forecasting
CONUS	continental United States
DEVCOM	US Army Combat Capabilities Development Command
LES	Large Eddy Simulation
MET	Model Evaluation Tools
METplus	METplus Wrappers
MetPy	collection of tools in Python for weather data
MSA	Multipurpose Sensing Area
NetCDF	network Common Data Form
NOAA	National Oceanic and Atmospheric Agency
NWP	Numerical Weather Prediction
NWS	National Weather Service
URMA	UnRestricted Mesoscale Analysis
WRF	Weather Research and Forecasting
WRF-LES	WRF with the Large Eddy Simulation option

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