THE ATMOSPHERIC MODEL EVALUATION TOOL: METEOROLOGY MODULE

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1. INTRODUCTION

Air quality modeling is continuously expanding in sophistication and function. Currently, air quality models are being used for research, forecasting, regulatory related emission control strategies, and other applications. Results from air-quality model applications are closely linked to the meteorological model that drives the dispersion, deposition, chemical transport, and chemical processes. Thus, modeling systems should be evaluated by considering all components/models involved (Hogrefe et al. 2001).

An Atmospheric Model Evaluation Tool (AMET), composed of meteorological and air quality components, is being developed to examine the error and uncertainty in the model simulations. AMET matches observations with the corresponding model-estimated values in space and time, and then stores the paired observation and model values in a relational database. Subsequent analysis programs extract user specified data from the database to generate statistical plots and tables. Many benefits are realized from using AMET.

1. Evaluation process is standardized
2. Large volume of evaluation results are easily managed
3. Overall evaluation process is more efficient and less labor intensive
4. Direct linkage between the meteorological and air quality model can be examined

An overview of the meteorological component of the AMET is presented in this note. This overview includes a discussion of the various components of the model evaluation system. Aspects of the observation-model matching module, evaluation database, and statistical analysis module are outlined. A discussion of AMET's future is also made.

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2. THE MODEL EVALUATION SYSTEM

AMET conforms to a specific framework that is composed of an observation-model matching module and a statistical analysis module, which are connected by a relational database. This framework is flexible, modular and efficient because it isolates the observation-model matching processes from the analysis processes. Rather than archiving the observation-model paired values (matched in space and time) in cumbersome text-based files, the matched pairs are stored in an easy-to-access relational database. AMET analysis programs, part of the statistical analysis module, independently access the database and generate various statistical plots given numerous user criteria. These statistics and plots are generated through a web-based user interface, but capability exists to generate them automatically via the *cronjob* utility on a UNIX-based platform. An additional utility allows users to develop an evaluation protocol that will generate a number of statistical plots with the same criteria for each model simulation with the "push of a button".

2.1 Observation-Model Matching Module

The observation-model matching module is the initial step in the evaluation process. The matching module cycles through each time step of the model output. At each model time step, the corresponding observations are collected. These observation records are read into memory including information such as the meteorological observation, station identification, network identification, elevation, and geographic position. The geographic position of the observation site along with the model domain information is used to calculate the grid index (i,j) of the model output that corresponds to the observation location. The user can specify that the model value is the nearest grid point of the model to the observation site (nearest neighbor), or bi-linear interpolation using the surrounding four model grid points. These model and observation values along with all other information about the observation are used to construct a database query that inserts the data into the evaluation database. This is repeated for each observation record and time step of the model output.

The meteorological component of AMET is currently compatible with three commonly used meteorological models, the National Centers for Environmental Prediction (NCEP) Eta model (Janjic, 1994), MM5 model (Grell et al., 1994), and Weather Research and Forecast model (WRF, Skamarock, 2005). The base model format required by AMET is NetCDF, which is the native output format of the WRF model. However, the MM5 model has a native binary format and the NCEP Eta model has a standard WMO GRIdded in Binary (GRIB) format. Subroutines have been incorporated to read these two model formats. In the case of MM5 a wrapper subroutine around a standard MM5 to NetCDF utility (available from NCAR) converts the raw MM5 output to NetCDF. A similar utility translates the Eta's GRIB-based datasets. These utilities allow the observation-model matching module to read the geographic projection specifications, variable dimensions, and variable data arrays from the model output.

Table 1 Meteorological variables that are evaluated for each observation class. Variable identification: T (temperature), Q (mixing ratio), U (u-wind component), V (v-wind component), PCP (hourly precipitation), SRAD (insolation), and PT (potential temperature).

Surface	Profiler	RAOB	Precipitation
T	U	PT	PCP
Q	V	RH	
U	T	U	
V		V	
PCP			
SRAD			

AMET's meteorological component utilizes a specific observational dataset, the Meteorological Assimilation Data Ingestion System (MADIS). MADIS is a relatively new (post July, 2001) integrated, reliable and easy-to-use database (MADIS Homepage, http://www-sdd.fsl.noaa.gov/MADIS) that has been developed by the National Oceanic and Atmospheric Administration's (NOAA) Forecast Systems Laboratory (FSL). The observational database consists of nearly every existing meteorological observation platform (surface, upper-air, wind profiler, satellite, and mesonet) on a real-time and historic basis. Currently, the AMET system utilizes surface-based, wind profiler, and rawinsonde upper-air observations from the MADIS database. For historical cases (pre-2001), a utility has been developed to convert standard National Center for Atmospheric Research (NCAR) TDL observations into hourly MADIS-type files. The system is flexible enough to read observations from other platforms or networks; however, these non-standard observations need to be externally re-formatted to a MADIS format. For example, data from a research wind profiler were converted to a MADIS wind profiler format and used in the AMET system.

Four main classes of observations are currently implemented in AMET: surface-based, rawinsonde, wind profiler, and precipitation. The MADIS surface-based observations (hourly) contain data from most of the surface observation networks in the United States including the U.S. government (NOAA, FAA) METAR, Surface Airway Observations (SAO), and Maritime/buoy networks. In addition, data from all meteorological meso-networks (RAWS, AWS, MesoWest, among others) in the government weather datastream are available. Additionally, SURFace RADiation (SURFRAD, http://www.srrb.noaa.gov/surfrad) observations, if present, are paired with model estimated downward shortwave radiation at the surface. The main surface-based meteorological variables that are evaluated are 2-m temperature, 2-m mixing ratio, 10-m wind speed and direction, hourly precipitation, and insolation as indicated in Table 1. There are typically about 10,000 hourly surface observations over the United States and surrounding countries in the MADIS database.

The NOAA Wind profiler network is the source of the second class of observations compared with model outputs by the AMET system. The wind profile data has two distinct platforms (http://www.profiler.noaa.gov/npn/aboutNpnProfilers.jsp). The first is the radio frequency (~400 MHz) profiler network, which provides wind speed and direction measurements throughout the troposphere at a vertical resolution of a few hundred meters. The lowest measurement level of the dataset is approximately 500 m. The second platform is the Radio Acoustic Sounding System (RASS), which uses Doppler shift information from sound waves to estimate the wind and temperature profile. These measurements have a much higher vertical resolution (~20 m), and the first level is below 100 m; however, the maximum measurement height is limited to 2000-3000 m. These data are merged to construct a single profile when platforms are co-located. Otherwise, each platform is compared to the model estimated profile separately. The observation-model matching module interpolates (linear) the observed profile to the model vertical levels. The primary variables matched are the u (west-east) and v (south-north) wind components; in the case of RASS observations, temperature is matched. A database query consisting of the observed and modeled pairs is constructed for each time and level, and inserted into the evaluation database. There are approximately 36 profile sites across the United States.

The third class of observations is the upper-air profile data (twice daily, 00 and 12 UTC) from the RAwinsonde OBservations (RAOB) network. This dataset includes approximately 100 sites in the United States, Canada and Mexico. These profile data span from the surface to the lower stratosphere. The observed profiles are interpolated (linear) to the model vertical levels, similar to the wind profiler observations. The meteorological variables compared are potential temperature, relative humidity and the wind components. The observed and simulated temperature profiles are converted to potential temperature. The relative humidity is calculated from the temperature and mixing ratio using standard formulas. Relative humidity is used as the moisture variable, to not only evaluate moisture content of the atmosphere, but also evaluate the simulated cloud cover.

The fourth class of observations used to evaluate meteorological model output is the gridded National Precipitation Analysis (NPA). The stage IV, multi-sensor, GRIB formatted dataset is used. These data are composed of Doppler radar derived hourly precipitation that is adjusted by *in-situ* rainfall measurements (gauge data). The process of interpolating this dataset to the model grid is done by a stand-alone program (external from the observation-model matching module). This program cycles through the hourly precipitation in the model output. During this process, the corresponding NPA grid is extracted from the GRIB file, interpolated to the model grid (area mean, determined by grid spacing of model) and along with the model grid values (total hourly precipitation), is stored in an AMET archive directory for subsequent analysis programs.

2.2 Relational Database

The “backbone” of the AMET framework is the relational database. The relational database used in the AMET system is MySQL, which is one of the most popular and widely used database servers. MySQL is considered open source, so it is freely distributed. New versions of MySQL have a parallel, multi-node capability for more intensive applications. The AMET database has been successfully tested with large annual datasets.

Many evaluation systems compare the model with observations and generate performance statistics in a one-step process. In some cases the observed-modeled paired values are not saved, only the statistics. In cases where the paired values are conserved, they are often stored in cumbersome text files, which can quickly become unmanageable, especially for longer simulations (e.g., annual or seasonal simulations). A benefit of the relational database is that the observed-modeled pairs along with other information about the observation (i.e.; site, latitude, longitude, elevation and landuse) are stored in a fashion that allows for easy retrieval by analysis programs. In addition, the database separates the observation-model matching process from the analysis process, which has the advantages of making the system modular, and allows the data to be accessed by non-AMET applications (Matlab, SAS, Excel and most other analysis packages). The relational database also allows the user to extract specific sub-set of data according to criteria, such as time of day, time of year, latitude-longitude, state, elevation, network type, land use, value of the variable, or/and any other variable. For example, all observed and modeled temperature pairs can be extracted for summer in North Carolina when the temperature is greater than 305 K (90º F), when wind direction is from the southwest, and wind speed less than 2 $m \cdot s^{-1}$. Furthermore, the relational database can be used to link different datasets like the air quality comparison results with the meteorology.

2.3 Statistical Analysis Module

The model evaluation is performed by the statistics analysis module of AMET, which is a collection of various programs that generate user controlled statistical plots. These programs require the user to provide criteria that determine the observation-model pairs used in an analysis. The database is then queried for that particular dataset, and then the specified statistics and plots are generated. This process can be done through a user-friendly web interface or by manually modifying configuration files and executing the programs by way of the command line.

Analysis programs exist for all the data classes. The current analysis types for surface-based data are a multi-panel evaluation plot, diurnal statistics, observation-model time series, spatially plotted statistics, precipitation and diurnal solar radiation. The multi-panel evaluation plot

(Figure 1) requires the user to specify an exact dataset to evaluate, using many available criteria. A plot consisting of a scatter plot of observation and model values, a table of performance statistics, statistics as a function of the observed range and a histogram of model error is produced. Additionally, the statistics are plotted for each variable as a function of time of day (diurnal plot). All statistics that are plotted are provided to the user in text format. This analysis method allows the user to isolate data by state, region, latitude, longitude, elevation, land use, observation network, date, time of day, temperature range, moisture range, wind speed or direction, precipitation amount, or any combination of these criteria.

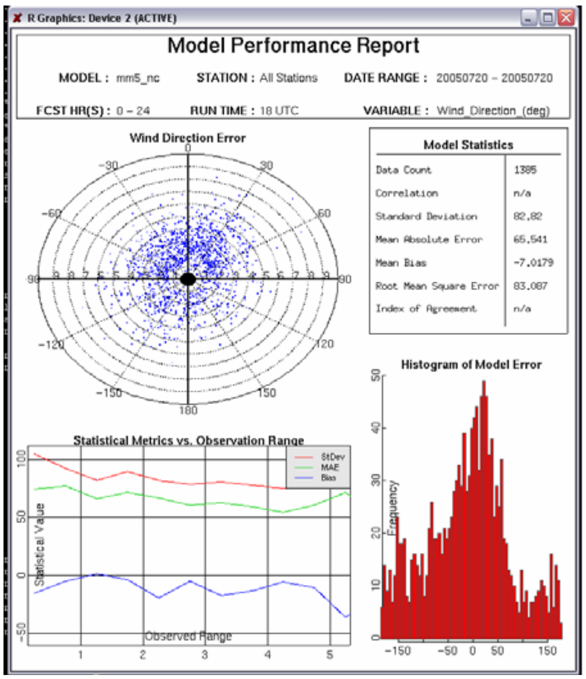

Figure 1 Multipanel evaluation plot of wind direction from AMET'.

Time series analysis (Figure 2) allows the user to examine the hour-to-hour performance of a meteorological simulation at a site or group of sites. For this analysis, the user specifies the observation site(s) and a period of interest. The program extracts the specified data from the database and generates a time series of 2-m temperature, 2-m mixing ratio, 10-m wind speed and direction. Bias, mean absolute error and index of agreement statistics are calculated and plotted on the time series for a quantitative perspective of the graphical comparison. Options exist to compare two different model simulations to the observations on the same plot, which aids model sensitivity studies.

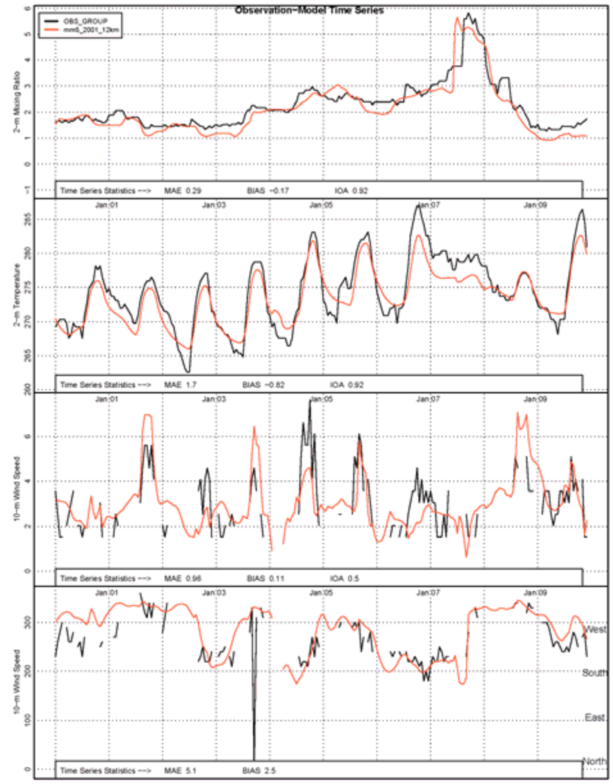

Figure 2 Timeseries comparison of observed and simulated 2-m mixing ratio, 2-m temperature, 10-m wind speed and 10-m wind direction at Raleigh-Durham Airport.

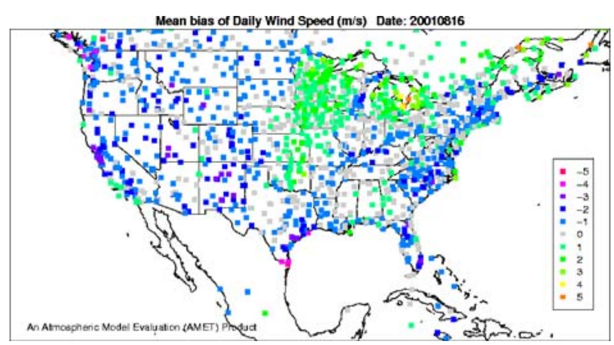

Figure 3 Spatial distribution of the mean bias of 2-m temperature from AMET's spatial statistics program.

Spatial plots (Figure 3) are generated by calculating statistics for each observation site in the model domain. Color-coded symbols (circles or squares), representative of the range of the statistical values of all stations, are plotted at the site locations on a geographic map. The program requires the user to specify a period of interest. Individual spatial plots are generated for each surface meteorological variable (same as the time series above), and for a number of statistical metrics including model bias, mean absolute error, root mean squared error, and index of agreement. This analysis is valuable to assess regional model performance.

The precipitation analysis is one of the most valuable of the available programs. This tool requires the user to specify a time period and precipitation threshold. The hourly files that fall within this time are opened, and the observed and simulated precipitation amounts are accumulated. Plots are then generated that provide the simulated and observed total precipitation, difference between model and observed precipitation, and a categorical statistics plot. The categorical statistic plot indicates model hits, misses, and false alarms as well as a table with other popular categorical statistics such as threat score, bias, probability of detection, false alarm rate and critical success index.

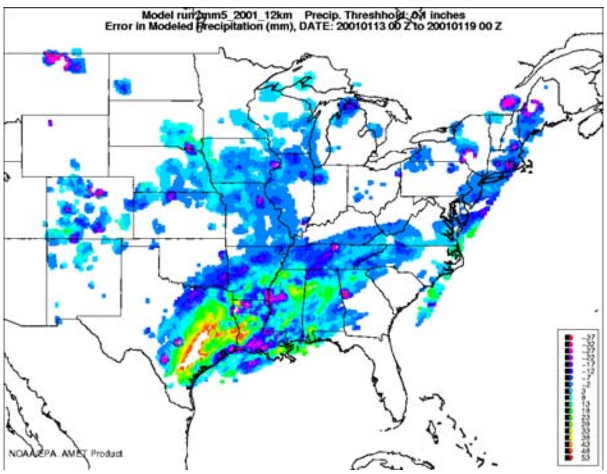

Figure 4 Difference between simulated and observed weekly precipitation from AMET's precipitation analysis program.

The wind profiler class of observed and modeled pairs has two different analysis programs. The first allows the user to specify a period, profiler site and maximum height. The data for these criteria are extracted and statistics (same as for the spatial statistics) are calculated as a function of time of day and height. The diurnal time series profile is generated for each statistic. Another approach is to choose a single day at a particular profiler site. When this is specified, a plot of the observed and simulated (overlaid) wind vectors is generated (Figure 5). These analyses are useful to determine model performance above the surface, especially throughout the planetary boundary layer where transport and dispersion are most important.

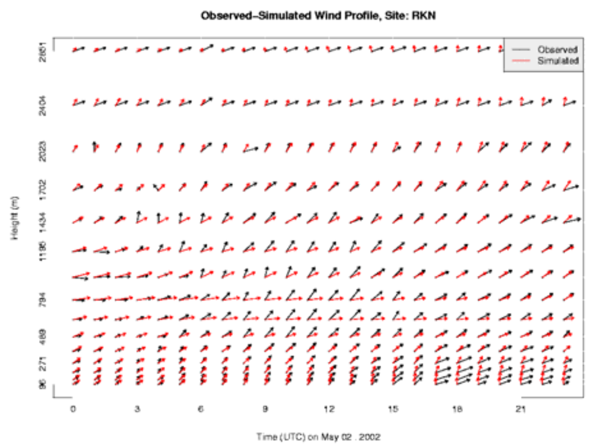

Figure 5 A comparison of simulated and observed wind vector profiles from AMET's wind profile analysis program.

Model performance above the near-surface layer can also be assessed using an analysis program that examines the model's ability to replicate the rawinsonde soundings. Two options are available 1) to examine a layer (height or pressure) average over a specified time (Figure 6), or 2) to average the profiles at a single site, over a specified date range. The first option provides a spatial plot of the temperature, relatively humidity, and wind speed bias at all sites in the domain. In addition, a layer-mean wind vector plot comparing the observed and simulated wind is generated.

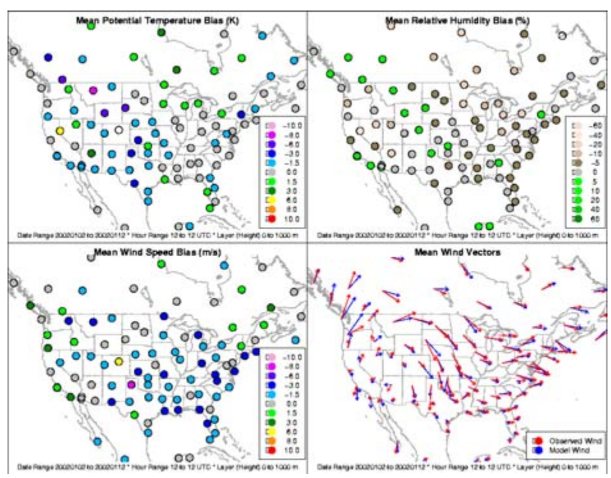

Figure 6 A comparison of simulated and observed potential temperature, relative humidity, wind speed, and wind vectors from AMET's RAOB analysis program.

3. INSTALLATION REQUIREMENTS AND FUTURE IMPROVEMENTS

The AMET meteorology module will be packaged and provided to the air quality community in late 2005 or early 2006. The evaluation system is UNIX-based, but most development has been done on a Linux platform. The observation-model matching module is coded in Perl script and requires several additional Perl modules (DBI, Mysql, PDL, PDL::NetCDF, and Date::Calc). The UNIX system must also have a MySQL server installed for the AMET evaluation database. Additionally, the MM5 to NetCDF programs (*examiner* and *archiver*) need to be independently compiled and placed in the main AMET executable directory, and if the Eta model is evaluated the GRIB program *wgrib* is required. Once all these components are made available, an "amet" user and group should be created on the UNIX system. Next, the AMET tar package should be un-tarred in the base "amet" user directory. The next step is to configure the MySQL server using a Perl-based MySQL configuration script. Once this has been done, a test/example script that matches a 6-hour MM5 dataset with observations should be executed to test the installation. At this point, the observation-model matching module and database is properly configured, and the test scripts can be modified to match the user's real model datasets to observations.

The statistical analysis component of AMET is based on the open source R statistical software and a number of easy to install R-modules (RMySQL, DBI, date, maps, mapdata, akima, RMET, ncdf). The installation of this component of AMET is done when the model-matching module is installed. However, it is necessary that the user properly install the R statistical package and additional R-modules on the UNIX system. These utilities should be made accessible from the amet user path. Furthermore, an apache web server is required to use the web-based interface. In order to configure the webserver correctly, the "http.conf" file (typically in the /etc/httpd/conf directory on Linux), needs to be modified for an amet virtual web server that points to /home/amet/www/amet. Once this is configured, the AMET website can be accessed to setup a new model evaluation project, interactively generate the observation-model matching scripts for new projects, or use the various interactive model evaluation tools. A weakness of the AMET system is that its installation is not a one-step process. However, once the system is installed, it can be a useful model evaluation tool.

Future improvements are planned for the AMET system. One of the more important improvements will be making certain processes more efficient through coding changes. AMET documentation will be improved in the near future by detailing each process, so others can participate in future development. Additional classes of observations will be used to compare with the models in the future. The MADIS observations database has several other potentially valuable sources including Aircraft Communications Addressing and Reporting System (ACARS) data, satellite derived wind, and Air Force Weather Agency gridded cloud analysis. In the future, AMET has the potential to allow multiple groups to share model evaluation results through a unified evaluation database.

Disclaimer- The research presented here was performed under the Memorandum of Understanding between the U.S. Environmental Protection Agency (EPA) and the U.S. Department of Commerce's National Oceanic and Atmospheric Administration (NOAA) and under agreement number DW 13921548. This work constitutes a contribution to the NOAA Air Quality Program. Although it has been reviewed by EPA and NOAA and approved for publication, it does not necessarily reflect their policies or views.

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