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MEMORANDUM

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BA MAC

From: Chris Emery, Edward Tai

Date: March 12, 2004

Subject: Standardization of MM5 statistical performance evaluation for CCOS applications

ENVIRON has recently completed a review and compilation of surface meteorological measurement data from the CCOS 2000 dataset that provides a sub-set of “standardized” observations throughout the state. The approach entailed identifying and extracting only those sites providing 10 m winds and 2 m temperature for the purposes of standardizing the meteorological performance evaluation among the various groups performing MM5 simulations for CCOS. Currently, data for the period spanning July 29 – August 2, 2000 have been compiled.

This technical memorandum describes the rationale for this activity and the components of the final dataset. We also discuss the concepts that have been adopted among air quality modelers across the U.S. for a rigorous meteorological performance evaluation approach, and describe a set of statistical measures that should be developed and reported relative to “benchmarks” for acceptable performance. Finally, we describe a program that can be used to calculate and graphically present these measures on hourly and daily time scales.

THE CCOS METEOROLOGICAL EVALUATION DATASET

The CCOS meteorological database includes measurement data taken during the summer of 2000 throughout central and northern California. Data from both existing routine networks and special study sites were collected at the surface and aloft, and are currently managed by the ARB. The names and locations of surface stations were compiled from the routine ARB/District-run (AIRS) sites, CIMIS, RAWS, NWS, and other various special sites and networks. We received an updated version of the CCOS meteorological dataset from the Bay Area District, as they had identified and fixed the coordinates of certain sites.

In further reviewing the CCOS surface meteorological dataset, we identified several issues that impact the quality and consistency of wind, temperature, and humidity measurements, which would therefore obfuscate our quantitative evaluation of MM5 performance. The key issues revolve around: (1) the various probe heights used among and within the various networks; (2) the maintenance status of certain networks (i.e., time since calibration, system checks, etc.); and (3) the lack of data population for the list of sites compiled for the CCOS meteorological

database.

We have recently received anecdotal evidence that data quality from the CIMIS network are likely sub-par. Our information suggests that most sites have not undergone routine calibration or maintenance for possibly several years. Furthermore, CIMIS sites comprise probes atop 2-m tripods as their focus is on irrigation management. Beyond the potential precision issue, a database populated with data from such a low-level probe configuration will generate a low wind bias.

In our experience, data from RAWS sites have been historically problematic. Used by fire and land managers, these sites are usually located in fire-prone areas in rural lands, and can often be located in valley floors or atop ridge lines in complex terrain. The standards for establishing these sites are not as rigid as NWS or District-run stations. RAWS incorporates a variety of mast and probe heights from one to several tens of meters; some sites are “mobile”. We have often seen that the anemometers possess high minimum wind thresholds as the sensors need to be rugged and durable since their purpose is to measure higher winds and gusts for fire weather.

Identifying sites by network in the CCOS dataset was difficult. We obtained a site list lookup table/description from the ARB, but meta data did not consistently contain all needed information to fully describe the sites, their mast heights, type of probes, the network to which they belong, etc. Once we began to extract meteorological measurements from the CCOS database, we found that it is missing all NWS data and all RAWS data (except for one site). We procured hourly NWS data for the July/August 2000 episode from ATMET.

We removed RAWS and CIMIS stations from inclusion into the MM5 evaluation dataset. Seven sites are located outside the domain in Southern California, and were removed. We included those ARB/District and other miscellaneous sites that explicitly meet the criteria for 10 m winds and 2 m temperature, as determined by information available in the CCOS station meta files or site names. If probe height information was missing for a given site, we assumed a 10 m wind mast and retained the wind observations (Saffet Tanrikulu, personal communication), but disregarded temperature and humidity observations from consideration. Most of these unlabelled sites were from the air quality districts. We also included all data from NWS stations.

A final complexity should be mentioned. The hourly NWS data are provided from automatic weather stations (ASOS) from numerous airports in California. They are recorded within ten minutes before the top of each hour, based on averaged conditions over a few minutes. Thus they should be considered “instantaneous” observations. Data logged by ARB/District sites are usually hourly-averaged. It is unknown what the time interval is for other miscellaneous sites retained for the MM5 evaluation dataset. The extent to which differences between instantaneous and averaged data will affect the MM5 performance evaluation is unclear. It should be noted that MM5 output is instantaneous at the top of each hour, which most closely matches the format of the NWS observations. This is a key reason (besides consistent site configuration) that ATMET utilizes only standard NWS observations in their evaluation of

meteorological models.

The resulting MM5 evaluation dataset includes 242 sites. The data were stratified into the eight CCOS analysis regions shown in Figure 1, which was first proposed by the ARB. The data have been formatted into the RAMS RALPH v2 format, which is one of two allowable input formats for ENVIRON's METSTAT software. METSTAT also reads observation data in the MM5 binary FDDA format. We chose the RALPH format as it readable ASCII text and is relatively self-documenting.

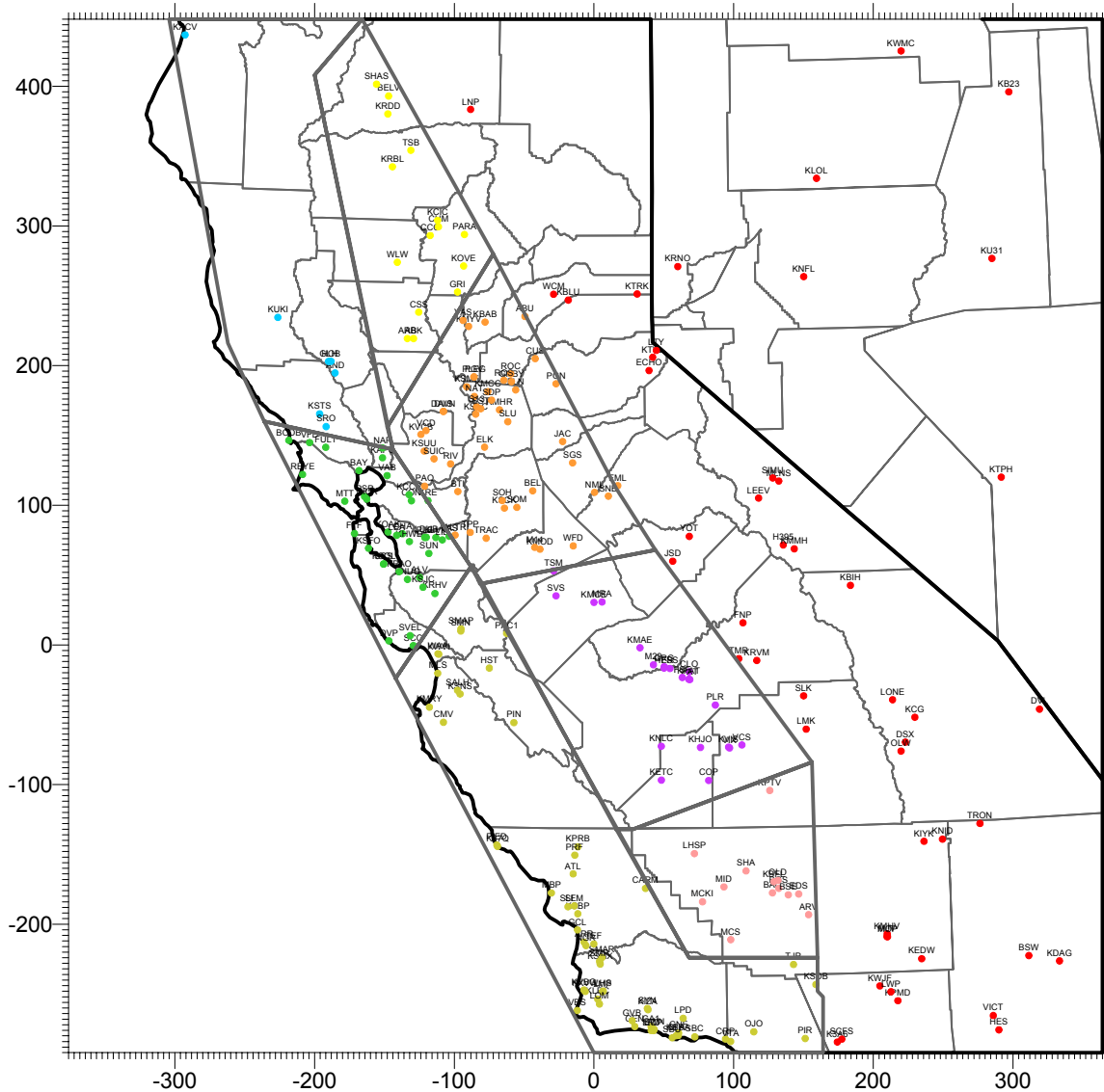


Figure 1. Location of meteorological data sites included in the July/August 2000 CCOS meteorological model evaluation dataset.

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An example of the RALPH data format is shown below. The data are space delimited to allow for Fortran free-format list-directed read. The data records are ordered first by site, then by time.

```

999999 2
4
WINDSPEED m/s
WIND_DIRECTION deg
TEMPERATURE K
MIX_RATIO g/kg
1999 09 13 0000 WRCC3811      35.590 -88.910  0.   1.54 000 270. 000 302.6 000  9.66 000
1999 09 13 0000 WRCC3866      32.550 -88.560  0. -999.00 000 -999. 000 300.4 000 17.00 000
1999 09 13 0000 WRCC3904      30.580 -96.360  0.   0.00 000   3. 000 307.0 000 12.01 000
1999 09 13 0000 WRCC3927      32.890 -97.040  0.   3.09 000 110. 000 308.2 000 11.69 000
1999 09 13 0000 RAOB72240      30.120 -93.220  0.   0.00 000   5. 000 302.6 000 15.19 000
1999 09 13 0000 WRCC3940      32.310 -90.070  0.   2.06 000 100. 000 302.6 000 14.32 000
1999 09 13 0000 WRCC12912      28.860 -96.920  0.   5.66 000 130. 000 302.6 000 15.28 000
1999 09 13 0000 WRCC12916      29.990 -90.250  0.   2.06 000  70. 000 300.9 000 20.04 000
:
:
:

```

- Record 1: A marker (999999) denoting the beginning of a new file or new section of a file, and RALPH version number (2)
- Record 2: Number of variables on file for each observation
- Record 3+: Specific variable names and units; allowed names/units are (note that these are case-sensitive):
- WINDSPEED, m/s, knots, mph, km/hr
 - WIND_DIRECTION, deg
 - TEMPERATURE, C, F, K
 - MIX_RATIO, g/g, kg/kg, g/kg
 - DEWPOINT, C, F, K
 - REL_HUMIDITY, %, fraction
 - STN_PRES, Pa, mb, in

Each Observation Record:

- 4-digit year
- 2-digit month
- 2-digit date
- 4-digit UTC data time
- 8-character station ID
- real station latitude
- real station longitude
- real station elevation (not used by METSTAT)
- real/integer pairs of data values and quality flags (METSTAT ignores the quality flags, missing values are -999.0)

There must be as many value/flag pairs as specified in the header. Values are in the order specified in the header and are of the specified units. Wind direction is Earth-relative, not rotated to the meteorological model projection.

PERFORMANCE EVALUATION METHODOLOGY

The goal of the MM5 model evaluation should be to (a) assess whether and to what extent confidence may be placed in the modeling system to provide three-dimensional wind, temperature, moisture, and turbulent mixing rates to air quality models, and (b) compare and contrast performance against results obtained from previous meteorological model applications across the country. The basis for the assessment is a comparison of the predicted meteorological fields to available surface and aloft data collected by the National Weather Service and other reporting agencies. A specific set of statistics has been identified for use in establishing benchmarks for acceptable model performance, with the idea that these benchmarks, similar to current EPA guidance criteria for air quality model performance, allow for a consistent comparison of various meteorological simulations for important variables at the surface and in the boundary layer.

A number of recent studies describe the theoretical formulation and operational features of the MM5 model (see, for example, Dudhia, 1993; Grell et al., 1994; Seaman, 1995, 1996, 2000; Pielke and Pearce, 1994; Seaman et al., 1997) and discuss its performance capabilities under a range of atmospheric conditions (e.g., Cox et al., 1998; Hanna et al., 1998; Seaman and Michelson, 1998; Seaman et al., 1992, 1995, 1996; Seaman and Stauffer, 1996; Tesche and McNally, 1993, 1996; McNally and Tesche, 1996, 1998; Tesche et al., 1997, 2001a,b; Emery and Tai, 2001; Emery et al., 2001, 2002, 2003; Yarwood et al., 2003; ATMET, 2003a,b,c). The results of the present analyses should add to this body of knowledge.

Evaluation Philosophy

The following discussion is taken from Tesche (1994) and Tesche et al. (2001b). We emphasize that the term "modeling system" refers to the main MM5 source code, its preprocessor and data preparation programs, the "mapping" routines that translate MM5 output to CAMx input, and the supporting data base. Ideally, a comprehensive evaluation of the MM5 model would include the seven steps outlined by Tesche (1994). Such an intensive evaluation process is rarely, if ever, carried out due to time, resource and data base limitations. Nevertheless, it is useful to identify the ideal evaluation framework so that the results of the current evaluation can be judged in the proper perspective. This also allows one to set realistic expectations for the reliability and robustness of the actual evaluation findings.

As described by Tesche (1994) a rigorous model evaluation consists of two components: an *operational evaluation* and a *scientific evaluation*. The operational evaluation entails an assessment of the model's ability to correctly estimate surface and boundary layer wind, temperature, and mixing ratios largely independent of whether the actual process descriptions in the model are accurate. The operational evaluation essentially tests whether the predicted meteorological fields are reasonable, consistent, and agree adequately with available observations in time and space. In this study, the operational evaluation focuses on the model's ability to reproduce hourly wind speed, wind direction, temperature, and moisture observations across the modeling domain. The operational evaluation procedures to be used

here include those employed in other prognostic model evaluations (see, for example, Emery et al., 2001, and Tesche et al., 2001b), including regional modeling currently being conducted by WRAP, VISTAS, MRPO, and LADCO. The operational evaluation provides only limited information about whether the results are correct from a scientific perspective or whether they are the fortuitous product of compensating errors; thus a “successful” operational evaluation is a necessary but insufficient condition for achieving a sound, reliable performance testing exercise. An additional, scientific evaluation is also needed.

The scientific evaluation addresses the realism of the meteorological processes simulated by the model through testing the model as an entire system as well as its component parts. The scientific evaluation seeks to determine whether the model's behavior, in the aggregate and in its component modules, is consistent with prevailing theory, knowledge of physical processes, and observations. The main objective is to reveal the presence of bias and internal (compensating) errors in the model that, unless discovered and rectified, or at least quantified, may lead to erroneous or fundamentally incorrect technical or policy decisions. Ideally, the scientific evaluation consists of a series of diagnostic and mechanistic tests aimed at: (a) examining the existence of compensatory errors, (b) determining the causes of failure of a flawed model, (c) stressing a model to ensure failure if indeed the model is flawed, (d) providing additional insight into model performance beyond that supplied through routine, operational evaluation procedures.

Unfortunately, a scientific evaluation of the MM5 model is not possible with the data sets available in this project due to the absence of the specific measurements needed to test the process modules (e.g., soil moisture, Reynold's stress measurements, turbulence measures, and so on). Accordingly, our evaluation is limited to operational testing of the model's primary meteorological outputs (i.e., wind speed, wind direction, temperature, and moisture). This evaluation is further constrained by the fact that a portion of the observational information (wind speed and direction) is used directly in the data assimilation scheme to produce the model's three-dimensional, time dependent fields.

Operational Evaluation for CCOS Applications

Output from MM5 is compared against meteorological observations from the various networks operating in California and throughout the western U.S. This is carried out both graphically and statistically to evaluate model performance for winds, temperatures, humidity, and the placement, intensity, and evolution of key weather phenomena. The focus of this evaluation centers on performance in the 4-km grid. However, a regional qualitative analysis should also be carried out in the 36- and 12-km MM5 domains. The problem with evaluating statistics is that the more data pairings that are summarized in a given metric, the better the statistics generally look, and so calculating a single set of statistics for a very large area (e.g., the entire 36-km domain) would not yield significant insight into performance. Therefore, the statistical analysis is refined to sub-regions within the large 4-km grid. Results from the sub-regional evaluations give clues as to any necessary modifications to be made in the MM5 configuration. Specifically, wind profiler measurements in California provide a very good time-resolved

source of data in the vertical, and are used to compare to MM5 output.

The first step in the operational evaluation is the preparation of graphics to display the predicted meteorological fields at the surface and for selected levels aloft. This allows for a qualitative assessment of model performance by comparing results to commonly available analysis maps of wind, temperature, pressure, and precipitation patterns available from several entities, including the NWS and others (e.g., <http://weather.unisys.com>). The purpose of these evaluations is to establish a first-order acceptance/rejection of the simulation in adequately replicating the gross weather phenomena in the region of interest. Thus, this approach screens for obvious model flaws and errors.

Statistical Evaluation

Several statistical measures are calculated as part of the meteorological model evaluation. Additional plots and graphs are used to present these statistics on both hourly and daily time frames. These measures are calculated for wind speed, wind direction, temperature, and humidity at the surface and in the boundary layer. Below we list and describe the various statistical measures that should be identified in the study protocol.

The statistics used to evaluate meteorological model performance are all given in absolute terms (e.g., wind speed error in m/s), rather than in relative terms (percent error) as is commonly shown for air quality assessments. The major reason for this is that a very different significance is associated with a given relative error for different meteorological parameters. For example, a 10% error for wind speed measured at 10 m/s is an absolute error of 1 m/s, a minor error. Yet a 10% error for temperature at 300 K is an absolute error of 30 K, a ridiculously large error. On the other hand, pollutant concentration errors of 10% at 1 ppb or 10 ppm carry practically the same significance.

Mean Observation (M_o): calculated from all sites with valid data within a given analysis region and for a given time period (hourly or daily):

$$M_o = \frac{1}{IJ} \sum_{j=1}^J \sum_{i=1}^I O_j^i$$

where O_j^i is the individual observed quantity at site i and time j , and the summations are over all sites (I) and over time periods (J).

Mean Prediction (M_p): calculated from simulation results that are interpolated to each observation used to calculate the mean observation (hourly or daily):

$$M_p = \frac{1}{IJ} \sum_{j=1}^J \sum_{i=1}^I P_j^i$$

where P_j^i is the individual predicted quantity at site i and time j . Note that mean observed and

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predicted winds are vector-averaged (for east-west component u and north-south component v), from which the mean wind speed and mean resultant direction are derived.

Least Square Regression: performed to fit the prediction set to a linear model that describes the observation set for all sites with valid data within a given analysis region and for a given time period (daily or episode). The y-intercept a and slope b of the resulting straight line fit are calculated to describe the regressed prediction for each observation:

$$\hat{P}_j^i = a + bO_j^i$$

The goal is for a 1:1 slope and a “0” y-intercept (no net bias over the entire range of observations), and a regression coefficient of 1 (a perfect regression). The slope and intercept facilitate the calculation of several error and skill statistics described below.

Bias Error (B): calculated as the mean difference in prediction-observation pairings with valid data within a given analysis region and for a given time period (hourly or daily):

$$B = \frac{1}{IJ} \sum_{j=1}^J \sum_{i=1}^I (P_j^i - O_j^i)$$

Gross Error (E): calculated as the mean *absolute* difference in prediction-observation pairings with valid data within a given analysis region and for a given time period (hourly or daily):

$$E = \frac{1}{IJ} \sum_{j=1}^J \sum_{i=1}^I |P_j^i - O_j^i|$$

Note that the bias and gross error for winds are calculated from the predicted-observed residuals in speed and direction (not from vector components u and v). The direction error for a given prediction-observation pairing is limited to range from 0 to $\pm 180^\circ$.

Root Mean Square Error (RMSE): calculated as the square root of the mean squared difference in prediction-observation pairings with valid data within a given analysis region and for a given time period (hourly or daily):

$$RMSE = \left[\frac{1}{IJ} \sum_{j=1}^J \sum_{i=1}^I (P_j^i - O_j^i)^2 \right]^{1/2}$$

The RMSE, as with the gross error, is a good overall measure of model performance. However, since large errors are weighted heavily (due to squaring), large errors in a small subregion may produce a large RMSE even though the errors may be small and quite acceptable elsewhere.

Systematic Root Mean Square Error (RMSE_s): calculated as the square root of the mean squared difference in *regressed* prediction-observation pairings within a given analysis region

and for a given time period (hourly or daily):

$$RMSE_s = \left[\frac{1}{IJ} \sum_{j=1}^J \sum_{i=1}^I (\hat{P}_j^i - O_j^i)^2 \right]^{1/2}$$

where the regressed prediction is estimated for each observation from the least square fit described above. The $RMSE_s$ estimates the model's linear (or systematic) error; hence, the better the regression between predictions and observations, the smaller the systematic error.

Unsystematic Root Mean Square Error ($RMSE_U$): calculated as the square root of the mean squared difference in prediction-regressed prediction pairings within a given analysis region and for a given time period (hourly or daily):

$$RMSE_U = \left[\frac{1}{IJ} \sum_{j=1}^J \sum_{i=1}^I (P_j^i - \hat{P}_j^i)^2 \right]^{1/2}$$

The unsystematic difference is a measure of how much of the discrepancy between estimates and observations is due to random processes or influences outside the legitimate range of the model.

A "good" model will provide low values of the RMSE, explaining most of the variation in the observations. The systematic error should approach zero and the unsystematic error should approach RMSE since:

$$RMSE^2 = RMSE_s^2 + RMSE_U^2$$

It is important that RMSE, $RMSE_s$, and $RMSE_U$ are all analyzed. For example, if only RMSE is estimated (and it appears acceptable) it could consist largely of the systematic component. This error might be removed through improvements in the model inputs or use of more appropriate options, thereby reducing the error transferred to the photochemical model. On the other hand, if the RMSE consists largely of the unsystematic component, this indicates that further error reduction may require model refinement (new algorithms, higher resolution grids, etc.), or that the phenomena to be replicated cannot be fully addressed by the model. It also provides error bars that may be used with the inputs in subsequent sensitivity analyses.

Index of Agreement (IOA): calculated following the approach of Willmont (1981). This metric condenses all the differences between model estimates and observations within a given analysis region and for a given time period (hourly and daily) into one statistical quantity. It is the ratio of the total RMSE to the sum of two differences – between each prediction and the observed mean, and each observation and the observed mean:

$$IOA = 1 - \left[\frac{IJ \cdot RMSE^2}{\sum_{j=1}^J \sum_{i=1}^I |P_j^i - M_o| + |O_j^i - M_o|} \right]$$

Viewed from another perspective, the index of agreement is a measure of the match between the departure of each prediction from the observed mean and the departure of each observation from the observed mean. Thus, the correspondence between predicted and observed values across the domain at a given time may be quantified in a single metric and displayed as a time series. The index of agreement has a theoretical range of 0 to 1, the latter score suggesting perfect agreement.

Statistical Benchmarks

The Texas Natural Resource Conservation Commission (TNRCC) sponsored an MM5 modeling project in which we derived and proposed a set of daily performance “benchmarks” for typical meteorological model performance. These standards were based upon the evaluation of a variety of about 30 MM5 and RAMS air quality applications in the last few years, as reported by Tesche et al. (2001b). The purpose of these benchmarks was not necessarily to give a passing or failing grade to any one particular meteorological model application, but rather to put its results into the proper context. For example, expectations for modeling of the California coastal area might not be as high as a simpler domain located in the Midwest. The key to the benchmarks is to understand how poor or good the results are relative to the universe of other model applications run for California and other areas of the U.S. Certainly, an important criticism of the EPA guidance statistics for acceptable photochemical performance is that they are relied upon much too heavily to establish an acceptable (to the EPA) model simulation of a given area and episode. Often lost in the statistical evaluation is the need to critically evaluate all aspects of the model via diagnostic and process-oriented approaches. The same must be stressed for the meteorological performance evaluation.

Emery et al. (2001) carefully considered the appropriateness and adequacy of the proposed benchmarks based upon the results of MM5 simulations performed and reported in that study. Based upon these considerations, the final daily proposed benchmarks are given below:

<u>Wind Speed</u>	RMSE: < 2 m/s
	Bias: $< \pm 0.5$ m/s
	IOA: ≥ 0.6
<u>Wind Direction</u>	Gross Error: < 30 deg
	Bias: $< \pm 10$ deg
<u>Temperature</u>	Gross Error: < 2 K
	Bias: $< \pm 0.5$ K
	IOA ≥ 0.8
<u>Humidity</u>	Gross Error: < 2 g/kg
	Bias: $< \pm 1$ g/kg
	IOA: ≥ 0.6

The METSTAT Program

A statistical analysis software package has been developed to calculate and graphically present the statistics described above. The package is comprised of a single Fortran program (METSTAT) to generate observation-prediction pairings and to calculate the statistics, and a Microsoft Excel macro (METSTAT.XLS) that plots the results. Both of these are described here.

The Fortran program begins by reading user input options and input/output filenames, and then reads MM5 output prediction files and observational data files. This program is written in a modular form, which simplifies the inclusion of other routines to read output from other models, including RAMS or CAMx-ready files (planned as a near-term update). The program reads either MM5 observation FDDA input files directly, or observation data in an ASCII format.

The program then spatially and temporally pairs MM5 predictions with observations for a user-defined time and space window. Only surface-level data are used for the statistical calculations. Since the surface layer in MM5 is usually rather thick relative to the heights at which the observational data were recorded, the METSTAT program includes a micro-meteorological module that scales mid-layer predicted winds to 10 m heights, and mid-layer predicted temperatures to 2 m heights, using common stability-dependent similarity relationships. The horizontal analysis range can be given for an entire MM5 grid, by an LCP coordinate box, or as a list of specific site identifiers (such as WBAN or AIRS numbers), as labeled on the observational file. This allows for an evaluation at a single site, a subset of specific sites (e.g., those along a coastline that would be difficult to select by defining an LCP box) or over an entire regional domain.

The program then proceeds to calculate the statistics described above for each hour and for each day of the time window. The following parameters are determined:

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- Wind Speed, Temperature, Humidity:
 - Mean Observed
 - Mean Predicted
 - Bias
 - Gross Error
 - RMSE
 - RMSE_s
 - RMSE_U
 - IOA
- Wind Direction
 - Mean Observed
 - Mean Predicted
 - Bias
 - Gross Error

The RMSE and IOA have not been typically used to quantify error for wind direction, and thus are not calculated by the program.

Separate ASCII files containing the hourly and daily statistics are generated, formatted specifically to facilitate import into the Excel macro. The Excel macro is used to read the hourly and daily ASCII output files from METSTAT, and to plot the data. The hourly statistics are plotted as time series, to show the diurnal variation of model performance. The daily statistics are plotted as bar charts to show daily performance over an episode. The macro also allows the daily results from multiple MM5 runs to be plotted together to ease the inter-comparison of performance. Examples are shown in the figures below.

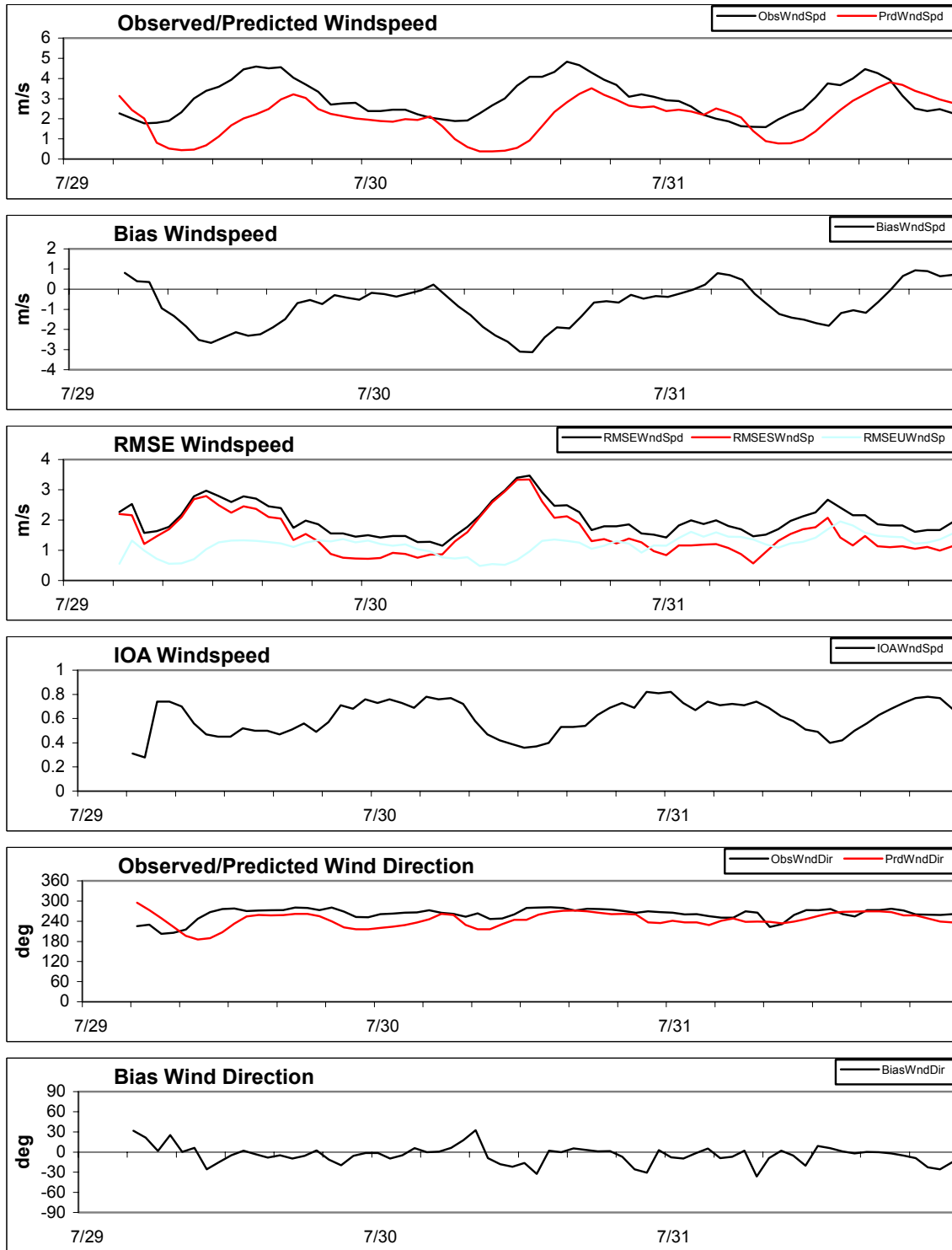


Figure 2. Example of hourly wind statistics for the SFBA sub-region from METSTAT. MM5 simulation is from a BAAQMD run using MRF and the NOAH LSM. Note that the phase shift in wind speed is typical when using the MRF boundary layer option.

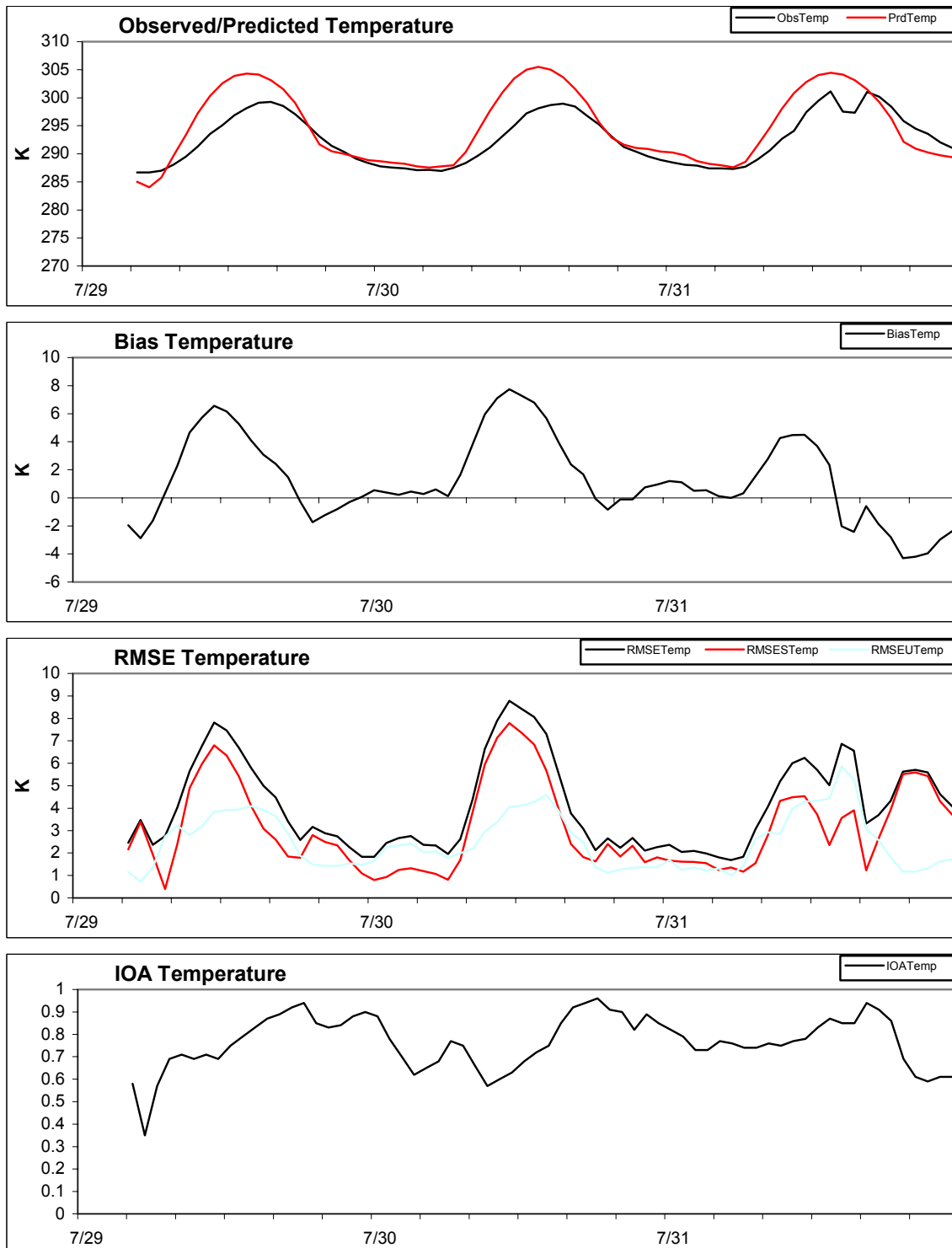


Figure 3. Example of hourly temperature statistics for the SFBA sub-region from METSTAT. MM5 simulation is from a BAAQMD run using MRF and the NOAH LSM.

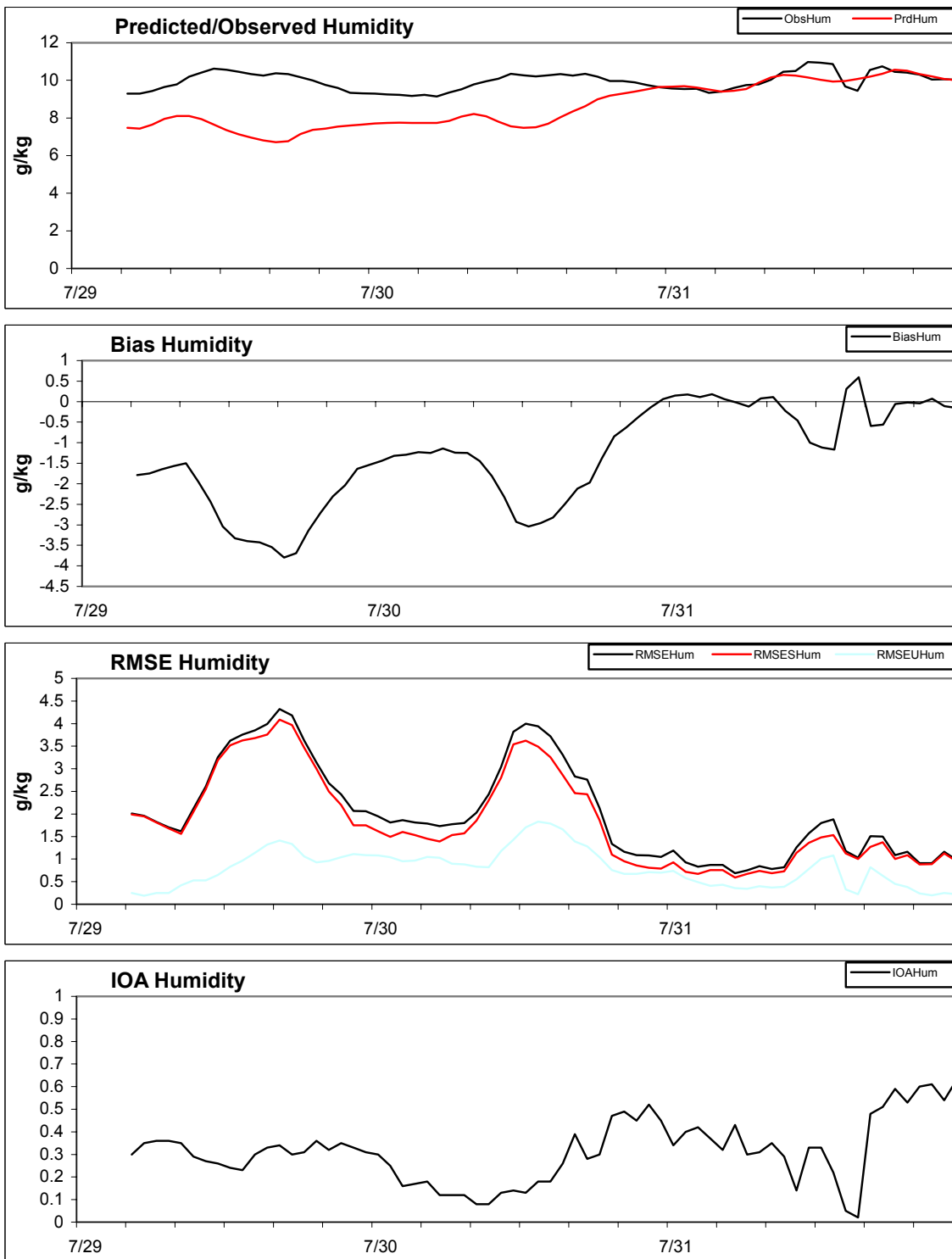


Figure 4. Example of hourly humidity statistics for the SFBA sub-region from METSTAT. MM5 simulation is from a BAAQMD run using MRF and the NOAH LSM.

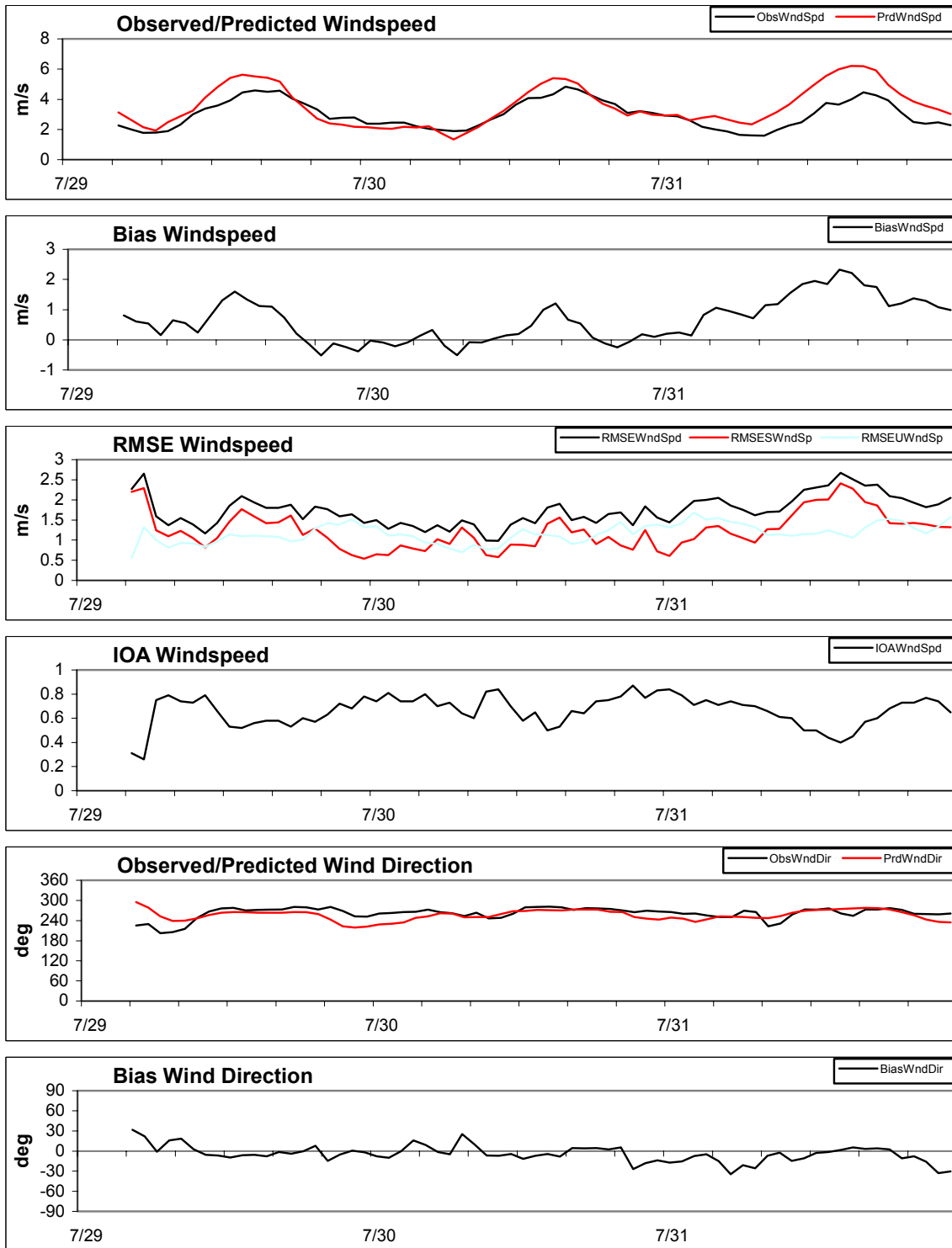


Figure 5. Example of hourly wind statistics for the SFBA sub-region from METSTAT. MM5 simulation is from a BAAQMD run using YSU boundary layer and the NOAH LSM. Note that the phase shift in wind speed is removed using YSU.

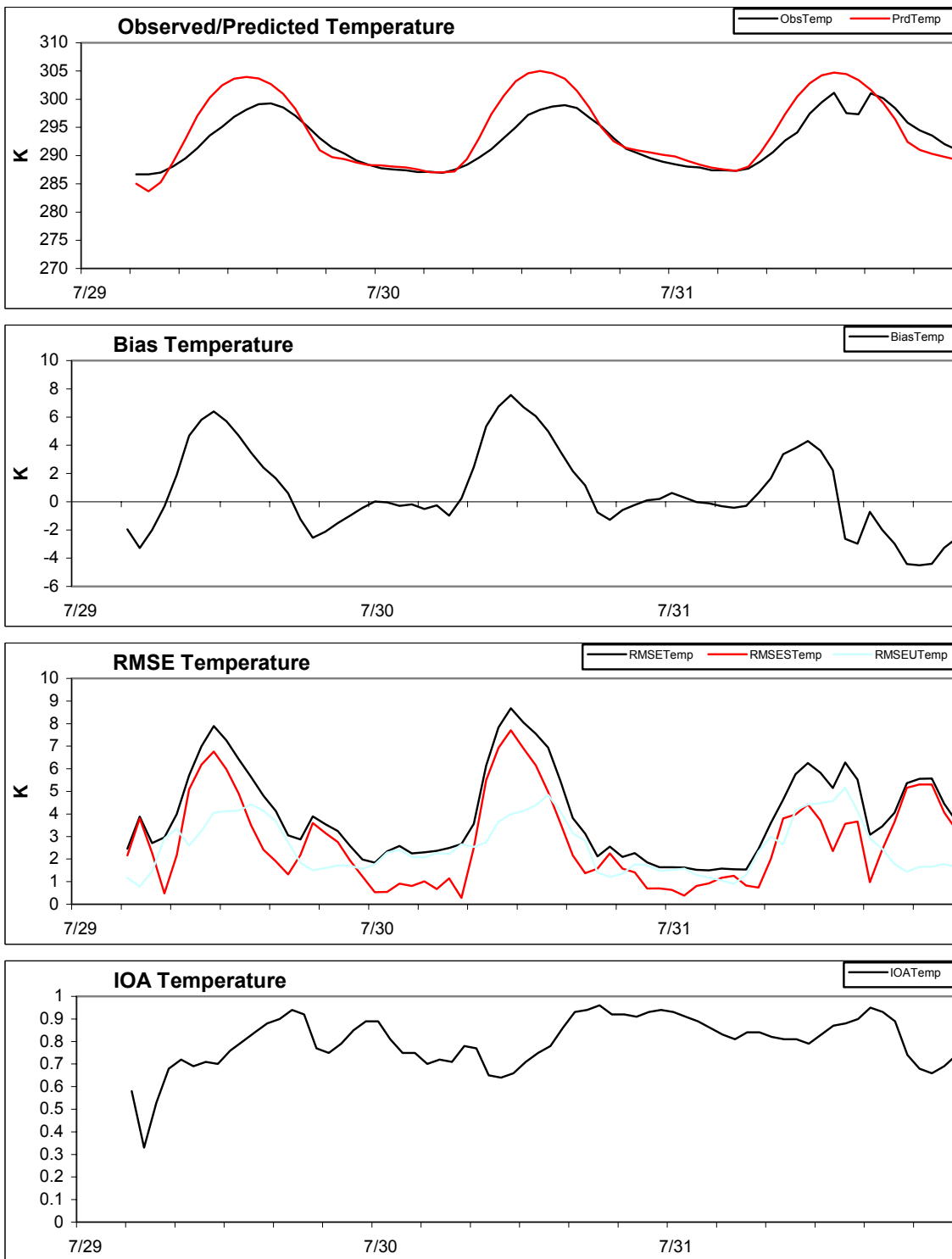


Figure 6. Example of hourly temperature statistics for the SFBA sub-region from METSTAT. MM5 simulation is from a BAAQMD run using YSU and the NOAH LSM.

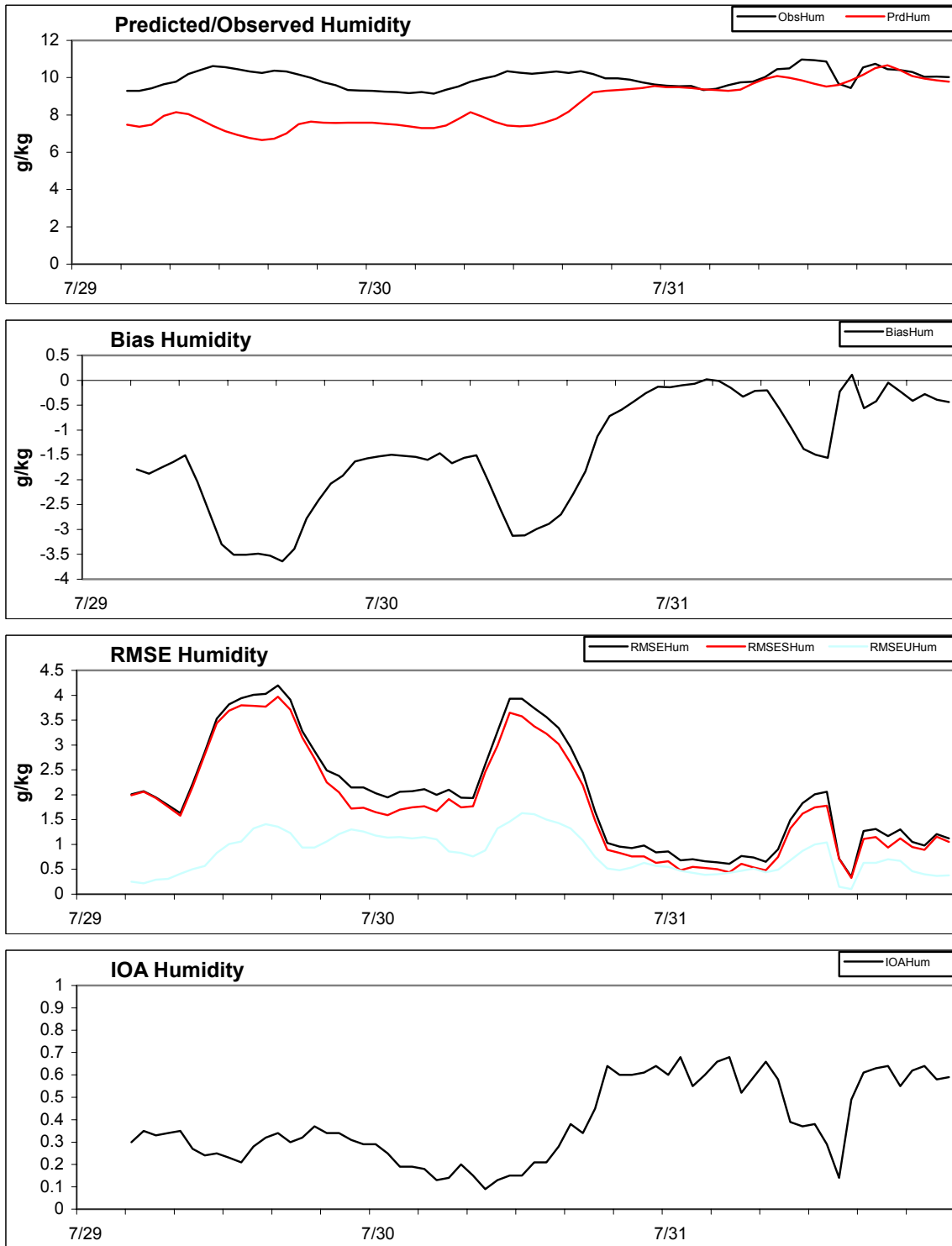


Figure 7. Example of hourly humidity statistics for the SFBA sub-region from METSTAT. MM5 simulation is from a BAAQMD run using YSU and the NOAH LSM.

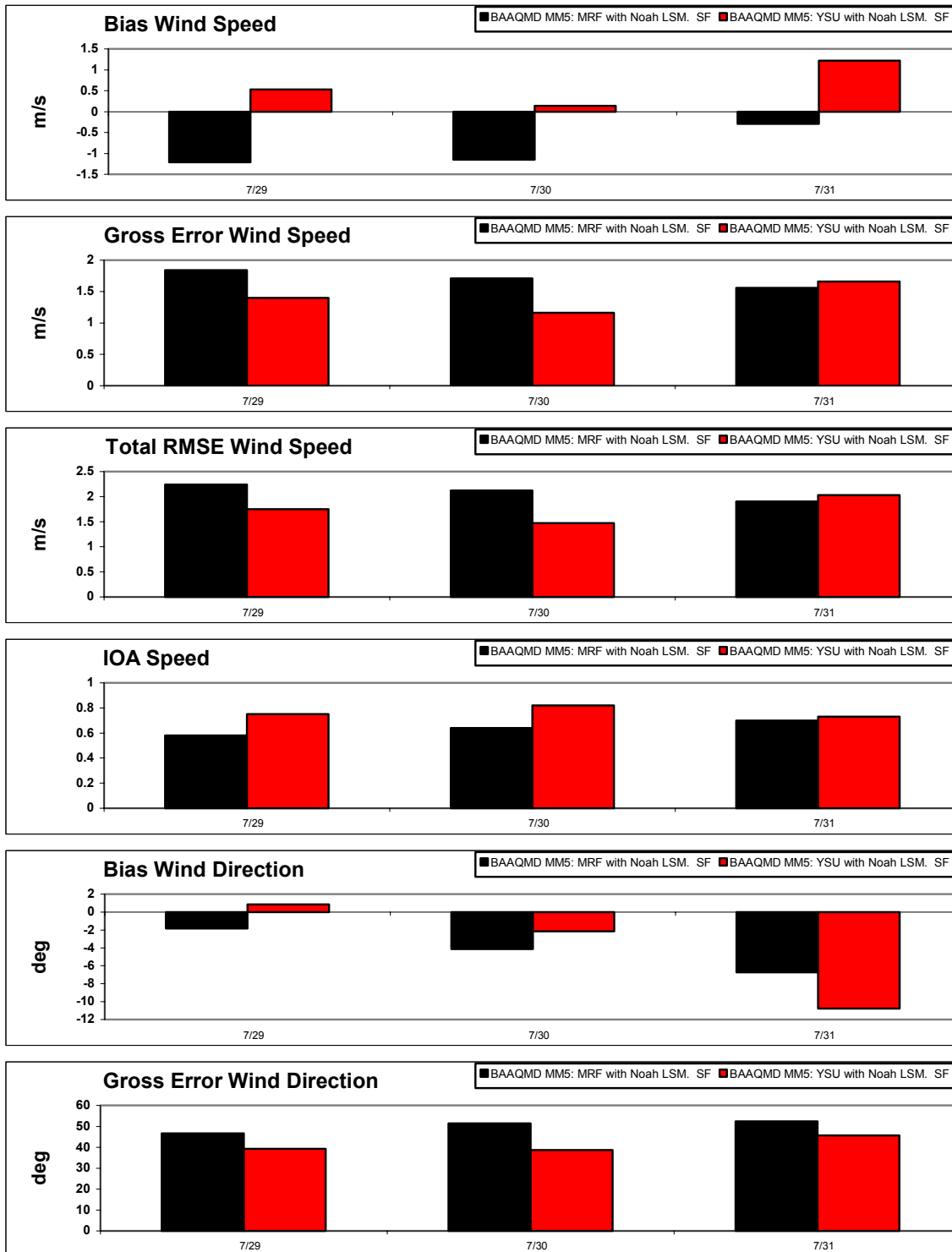


Figure 8. Example of daily wind statistics for the SFBA sub-region from METSTAT. Results from two BAAQMD MM5 simulations are shown using MRF and YSU boundary layer schemes with the NOAA LSM.

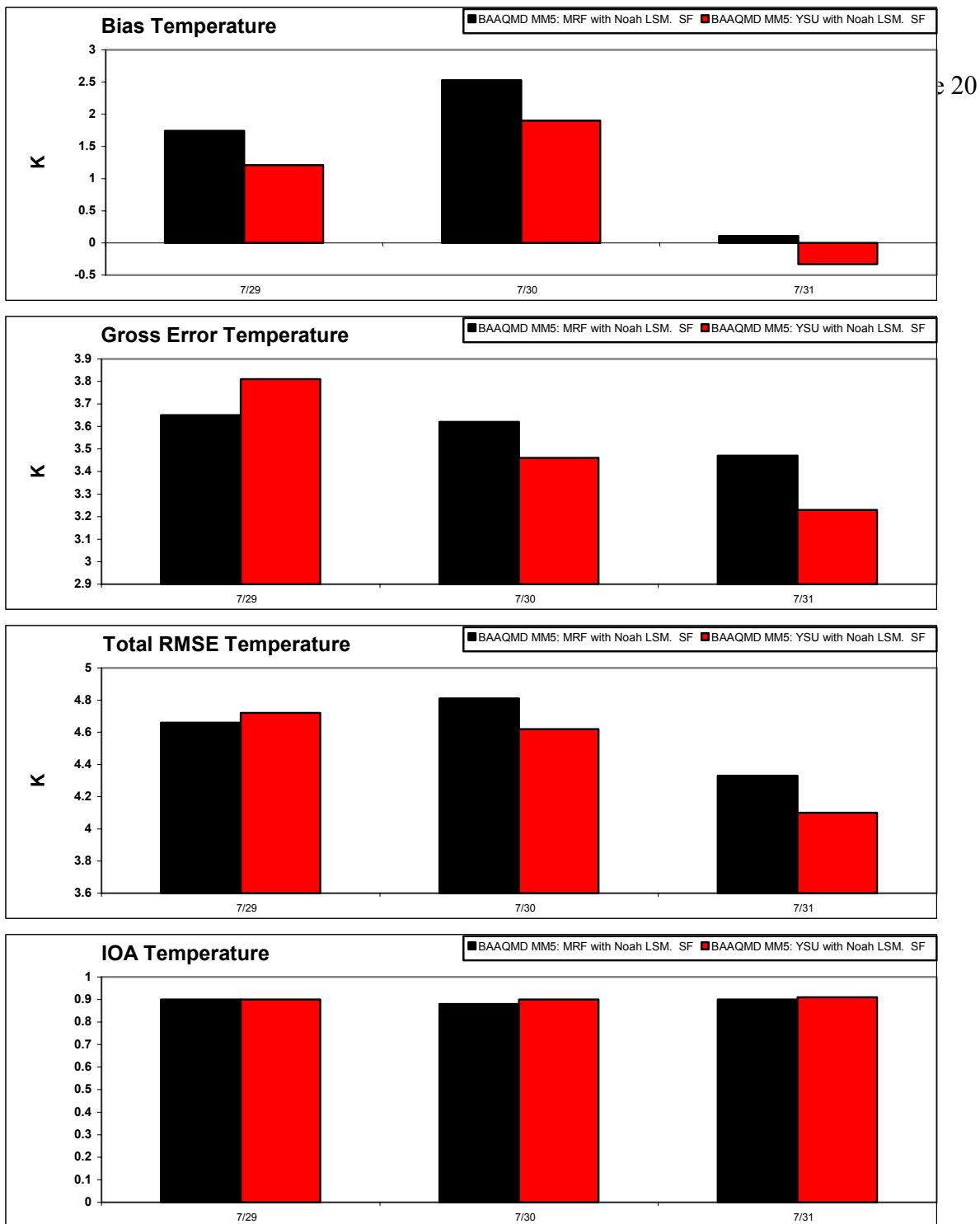


Figure 9. Example of daily temperature statistics for the SFBA sub-region from METSTAT. Results from two BAAQMD MM5 simulations are shown using MRF and YSU boundary layer schemes with the NOAH LSM.

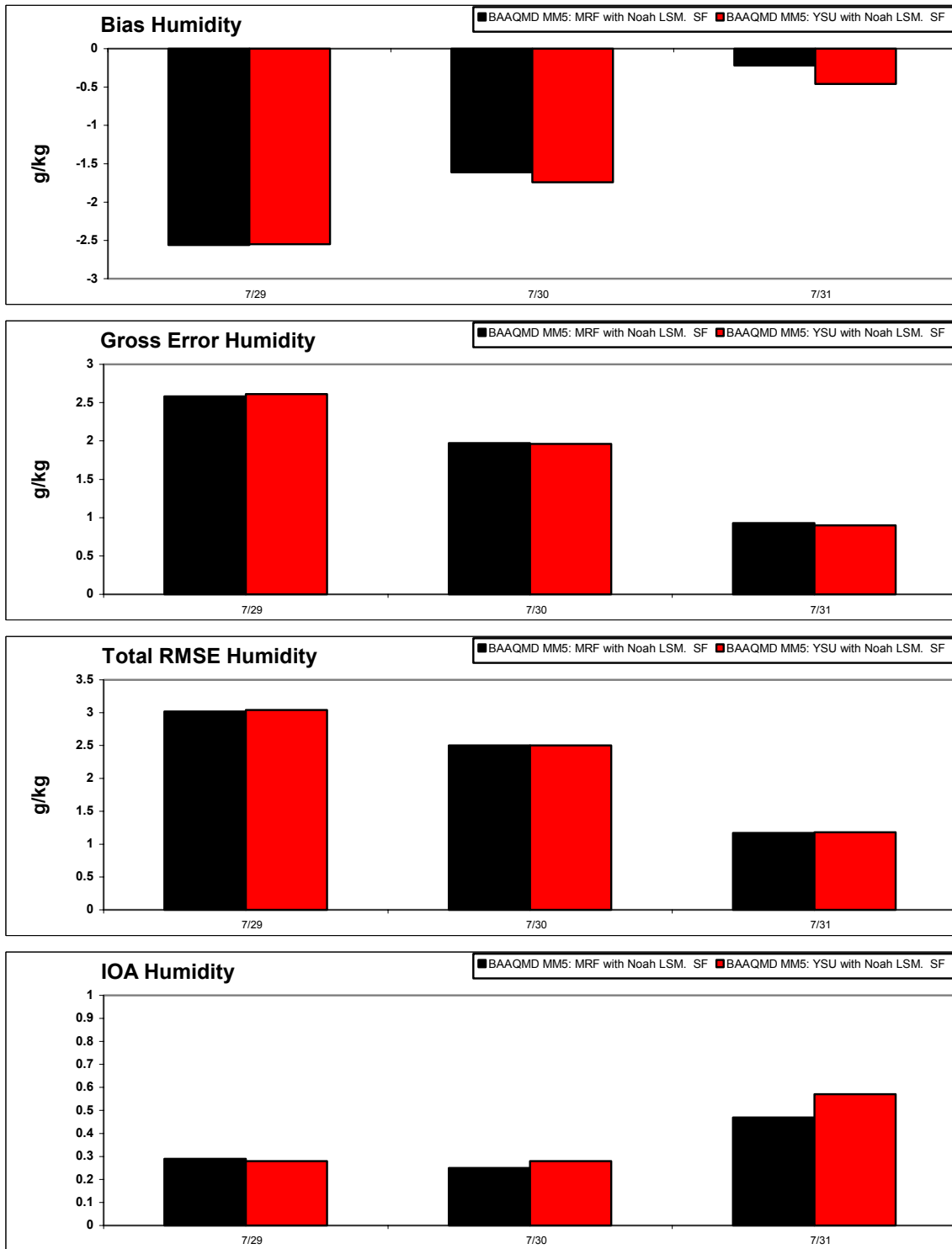


Figure 10. Example of daily humidity statistics for the SFBA sub-region from METSTAT. Results from two BAAQMD MM5 simulations are shown using MRF and YSU boundary layer schemes with the NOAA LSM.

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