Anthropogenic Moisture Effects on WRF Summertime Surface Temperature and Mixing Ratio Forecast Skill In Southern California

RICH F. COLEMAN
The Aerospace Corporation, Chantilly, Virginia

JAMES F. DRAKE AND MICHAEL D. MCATEE
The Aerospace Corporation, Omaha, Nebraska

LESLIE O. BELSMA
The Aerospace Corporation, El Segundo, California

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ABSTRACT

Mesoscale forecasts for the Los Angeles basin made with the fifth-generation Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model (MM5) exhibited a moderate to substantial warm temperature bias for extended periods in the summer months. A similar bias also was thought to exist in forecasts made using version 2.2 of the Weather Research and Forecasting Model (WRF v2.2). To address these biases, two sources of anthropogenic moisture were analyzed: commercial irrigation and outdoor domestic water use. These represent substantial amounts of equivalent precipitation that are not accounted for in normal WRF execution. This is especially true for the summer months when little or no precipitation occurs in the area. A method for estimating the temporal and spatial distributions of these two sources was developed and the resulting database was applied to model runs. The addition of these anthropogenic moisture sources is an important source of enthalpy, which results in significant cooling in WRF. However, in the course of the analysis it was determined that the biases in WRF were much smaller than had been thought. Also, despite producing significant cooling, the addition of anthropogenic moisture made only modest improvements in forecast skill, and only for some hours of the day, indicating that more research is necessary on how the physical processes are handled in WRF, and how the anthropogenic moisture is distributed during the forecast period.

1. Introduction

The Aerospace Corporation has made daily mesoscale forecast runs, initially using the fifth-generation Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model (MM5), for four years. The corporation recently has transitioned to the successor to MM5, and currently the daily forecast runs are being made with the Weather Research and Forecasting Model (WRF), specifically the Advanced Research WRF (ARW) physics core developed by the Mesoscale and Microscale Meteorology Division of the National Center for Atmospheric Research (NCAR). The Aerospace Corporation produces high spatial (5 km × 5 km) and temporal (hourly) resolution forecasts for a two-level nested domain over the southern California region (see Fig. 1).

The MM5 forecasts showed a persistent warm bias averaging between 1° and 2°C (depending on the model planetary boundary layer scheme), with a maximum overprediction in the late morning to early afternoon hours (McAtee et al. 2006). After the transition to ARW, a similar warm bias was observed in ARW forecasts. It was thought that in both cases, the warm bias could be attributed to insufficient latent heat flux due to the model failing to include moisture resulting from human activities. Research was undertaken to identify and quantify the sources of anthropogenic moisture in southern
California, and to develop a method of incorporating these moisture sources into the WRF modeling system.

As precipitation falls through the boundary layer and reaches the surface, it causes cooling in most circumstances. Also, precipitation that is cooler than the air or the surface will cause conductive cooling. Precipitation that falls through unsaturated air will partially or completely evaporate or sublime, causing cooling. This cooling can be substantial due to the very large latent heat of vaporization–sublimation of water ($2.5 \times 10^8$ J kg$^{-1}$ and $2.8 \times 10^6$ J kg$^{-1}$, respectively, at $0^\circ$C). Precipitation reaching the surface also will partially evaporate or sublime, causing the surface to cool, which then conductively cools the air. Many anthropogenic moisture sources (e.g., washing vehicles or irrigation with sprinklers) involve water drops passing through air in the boundary layer and/or reaching the surface. Other anthropogenic moisture sources (e.g., stock ponds or swimming pools) involve standing water. Both of these types of anthropogenic moisture sources will cause cooling in the boundary layer by the same physical mechanisms as natural precipitation. If the quantities of water involved are similar to natural precipitation amounts, then similar mesoscale weather effects will result.

Preliminary screening of the various types of human activity that add water to the environment identified three types that add water in amounts comparable to natural precipitation in the forecast area. As a result, it was hypothesized that the observed warm bias was a result of neglecting these sources of anthropogenic moisture, which are described below.

Due to the hot, dry summer climate, there is heavy use of water in the urban areas for watering lawns and plantings, washing automobiles, replenishing swimming pools, and other similar outdoor water-related activities. The population of the area is so large that a substantial amount of water is consumed by these various activities, which are collectively referred to here as domestic use, the first type of anthropogenic moisture. Similarly, the second type, commercial crop irrigation, consumes a very large amount of water in the inland valleys, except in the winter. Both of these sources act, in effect, like natural precipitation but are, of course, anthropogenic in nature.

This paper reports on the method developed to account for the effects of these two types of anthropogenic moisture in WRF and presents results showing the impacts on the surface temperature and mixing ratio forecast skill for southern California. It should be noted that the method used to incorporate anthropogenic moisture into WRF applies the moisture as a liquid at the surface, and so does not replicate actual precipitation. The third anthropogenic source is the moisture released into the atmosphere by the cooling towers of the several power plants located in southern California.

Section 2 provides details on the two types of anthropogenic moisture that are covered in this paper, including their spatial and temporal distributions, and the magnitude of the sources.

Section 3 describes the forecast modeling process used by The Aerospace Corporation for daily forecasts. Details of the domains used in the forecast are provided. The initialization and boundary conditions for the forecasts are described. The specific configuration used for the forecast model (WRF) is provided.

Section 4 addresses the impacts of including these moisture sources on the forecast skin temperature, and on the air temperature 2 m above the surface, by examining the differences in the forecast fields with and without the added moisture.

Section 5 provides verification results for forecasts run made daily for the period 1 July 2007–15 August 2007. A 36-h forecast was generated for each of the days in the period. Forecasts were made with and without the addition of anthropogenic moisture, and the skill of both types was determined by verification against surface observations at each forecast hour and averaged over all the days of the study.

Section 6 provides a summary of the results of the study.

2. Anthropogenic moisture sources

In attempting to quantify the amount of moisture added to the environment by human activities, a number of data
sources were found and used. To incorporate anthropogenic moisture into a mesoscale forecast model requires specifying the amount of water added to the environment, together with the spatial and temporal distributions of the added water. Unfortunately, there is no single database that includes all the required information, so it was necessary to create one from components in other databases. Each of the required constituents of this anthropogenic moisture database is described below.

a. Water consumption related to human activity

A number of data sources were reviewed that contain partial information on the amount of water consumed in various types of human activities. In the end, it was determined that the U.S. Geological Survey (USGS) was the most comprehensive source, providing annual water consumption data for all counties in the United States, organized by the type of activity. The compilation is performed by USGS every 5 yr. At the time this study was conducted, the most recent compilation was the one released in 2004 for the year 2000 (Hutson et al. 2004). The analysis described in this paper makes use of the USGS data from 2000.

b. Temporal variation in anthropogenic moisture

The USGS data quantify the amount of water used in each county in the United States, but only as an annual total. Ingesting anthropogenic moisture into WRF requires that the water be distributed on the forecast grid, in amounts appropriate to the forecast period. This necessitates allocating the water used in human activities to specific locations and at specific times. A number of approaches to this problem were assessed. Temporal variation is inferred using statistics on evapotranspiration regions in California. Spatial distribution, described in the next subsection, is inferred based on satellite-derived land-use categories.

The Office of Water Use Efficiency in the California Department of Water Resources (DWR), in cooperation with the University of California, Davis, manages a network of automated weather stations under the California Irrigation Management Information System (CIMIS) program. The CIMIS program was initiated in 1982 and has installed and operated 177 automated weather stations, of which 130 are currently active.

CIMIS automated stations collect data at 60-s intervals, and average them for hourly and daily periods. The data are uploaded daily to CIMIS’s central databases. The data are then ingested in an evapotranspiration model for two reference vegetation types: grass and alfalfa. The model computes daily evapotranspiration amounts, which are used by growers and large landscaping organizations to manage their irrigation. Details of the CIMIS program are available on the DWR Web site (DWR 2007).

Based on long-term studies of CIMIS data, DWR has compiled monthly and annual evapotranspiration amounts for a set of 18 zones that cover California. These zones are shown in Fig. 2. Many growers and large landscaping companies determine their irrigation amounts from the CIMIS data. As a result, there is good reason to expect that both commercial irrigation and domestic use, in the form of watering large landscape projects, track the CIMIS data. It was decided that monthly CIMIS evapotranspiration amounts, normalized by the annual total evapotranspiration, provided an acceptable way to allocate annual anthropogenic moisture to each month. As expected, the evapotranspiration fraction is strongly influenced by seasonal variation and, to a lesser extent, by the type of climate. Two examples are shown. The first example, in Fig. 3, shows the monthly evapotranspiration fraction for the zones that are found in Orange County, a typical coastal county. Figure 4 shows the monthly evapotranspiration fraction for the zones that are found in Imperial County, a hot inland desert county. The more moderate coastal climate is evident in Orange County, particularly in the summer.

c. Spatial distribution of anthropogenic moisture

The last step in creating an anthropogenic moisture database is to distribute the moisture spatially. This has been done using satellite-derived land-use information. While a number of such databases exist, it was decided to use the same land cover characterization (LCC) maps as are used in WRF, at the 30° resolution. The WRF LCC database is a version of the USGS Global Land Cover Characteristics dataset (USGS 2005). It provides land use globally at a spatial resolution of 30° (926 m) in 24 categories. Of these, there is one category for urban land use, and four categories of irrigated croplands, namely irrigated cropland and pasture, mixed dryland–irrigated cropland and pasture, cropland–grassland mosaic, and cropland–woodland mosaic. Irrigated and urban LCC pixels were mapped to California counties and to DWR evapotranspiration zones. The numbers of irrigated and urban pixels in each county that are in each evapotranspiration zone were calculated.

From this, an area-weighted, average monthly fraction of annual evapotranspiration was determined for each county, separately for both urban and irrigated land-use types. USGS annual amounts for commercial irrigation and domestic use were then multiplied by their respective monthly evapotranspiration fractions to determine the monthly amounts of anthropogenic moisture for each county. These amounts were assigned to each urban or irrigated pixel, in each county, as appropriate. It was
assumed that there would be equal amounts of the monthly anthropogenic moisture for each day in the month.

Plots of anthropogenic moisture, showing monthly average values of equivalent daily precipitation, in tenths of millimeters per day, are shown in Figs. 5 through 8, for the months of December, March, June, and September, respectively. As can be seen, there is a significant area that receives nonnegligible equivalent precipitation, especially in the summer, when natural precipitation averages less than 1.5 mm month$^{-1}$ over most of the domain.

FIG. 2. California evapotranspiration zones. (Reprinted courtesy of CIMIS.)
In fact, overall in California, 24 of the 58 counties have a combination of urban and irrigated area in excess of 10% of the total area of the county. Ten counties have a combination of urban and irrigated area of 25% or more of the total area of the county. Within the inner domain there are four counties, Kern, Imperial, Los Angeles, and Orange that have a combination of urban and irrigated area in excess of 10% of the total area of the county. Nearly all of the urban and irrigated area in California receives at least 1 mm day$^{-1}$ of equivalent precipitation, even in December.

3. Forecast domain and model description

a. Domain and model description

Version 2.2 of the ARW model was used in this study. It is configured to use theEta–TKE follow-on planetary boundary layer scheme, and the Noah land surface model, with temperature and moisture predicted in four soil layers. The 15-km-grid outer domain and 5-km-grid inner domain were initialized using terrain data derived from the 30’ USGS LCC dataset. One-way interaction was allowed from the outer to the inner domain. The model atmosphere uses 37 vertical levels, with a top pressure of 100 hPa. Short- and longwave radiation are parameterized using the Dudhia and the Rapid Radiative Transfer Model (RRTM) radiative transfer schemes, respectively (Dudhia 1989; Mlawer et al. 1997). Cloud and precipitation effects are modeled using the cumulus parameterization of Kain–Fritsch (Kain and Fritsch 1990, 1993; Kain 2004), and the WRF single-moment, five-class, microphysics scheme (Hong et al. 2004). The initial and lateral boundary conditions are provided by the National Centers for Environmental Prediction (NCEP) North American Model (NAM), at 40-km grid spacing.

b. Model modifications

By modifying the WRF Registry space was made available in WRF to hold the field of the spatially distributed anthropogenic liquid at the surface, for the middle of each month of the year, as well as the instantaneous field at each simulation time. The instantaneous field is derived from the monthly field by linear temporal interpolation. The WRF Preprocessing System (WPS) is used to ingest the anthropogenic liquid data and to interpolate them to the domain grids. WPS then puts the results into the WRF input file, from which WRF makes them available to the surface physics routines, where they appear as extra liquid flux only at the surface. As such, it enhances the surface evaporation and evapotranspiration, as well as accumulating on the surface, percolating into the soil, and adding to surface runoff. In this first attempt to represent the effects of anthropogenic moisture, it was specified as a steady source throughout each day.

Unlike MM5, WRF contains an urban canopy submodel that can be included or not. The results presented here were generated including the urban canopy submodel.

4. Comparison of surface fields with and without anthropogenic moisture

Prior to verifying the control (no anthropogenic moisture added) and modified (with added anthropogenic moisture) forecasts, the temperature and moisture fields of these cases were compared to determine whether ARW was sensitive to the addition of anthropogenic moisture. One representative example (4 July 2007) is presented to illustrate the general results. First, the available anthropogenic moisture [mg m$^{-2}$ day$^{-1}$ (mm day$^{-1}$)]
is shown in Fig. 9. The amount of moisture ranges from 20 to over $220 \text{ mg m}^{-2} \text{ day}^{-1}$, which is equivalent to 20 to $220 \text{ mm day}^{-1}$.

Because the largest amounts of anthropogenic moisture are added in the San Joaquin and Imperial Valleys, and because those areas are very hot (maximum temperatures $>40^\circ\text{C}$) and dry (dewpoint depressions of $20^\circ-30^\circ\text{C}$), the largest evaporative cooling occurs in these areas, especially during the daytime hours. Examination of atmospheric profiles of forecast temperature and dewpoint in these areas shows that even for the modified case they remain dry through the overnight hours, allowing evaporative cooling to occur throughout the forecast period.

Another effect is evident from examining these atmospheric profiles. A continuous humidification is seen at the lowest model layer in the modified case in the inland valleys (though the layer never becomes saturated), and it appears to result in reduced radiative cooling. Toward the end of the forecast period, this radiative effect appears to be larger than the evaporative cooling, resulting in slightly warmer overnight low temperatures in the modified case versus the control case.

For the coastal urban areas, less anthropogenic moisture is added than for the inland valleys and the atmosphere is typically cooler and moister, resulting in less evaporative cooling.

Figure 10 displays the difference between the skin temperature as modified by the addition of anthropogenic moisture and the skin temperature of the control run at the 22nd forecast hour, 2200 UTC (1500 Pacific daylight time, PDT). At this time there is strong evidence of differential cooling ($4^\circ-7^\circ\text{C}$ or more) over the irrigated areas at the northern boundary, as well as at the southeast corner of the domain. The cooling is much less over the areas of domestic water use, but is present there as well.

Figure 11 presents the differences in the surface temperature, considered at shelter height, for the two cases at the same time. The irrigated areas are cooler in the modified case compared to the control case, but the temperature difference and area of definite cooling are smaller than for skin temperature.

It was apparent after examining several forecast runs that the addition of anthropogenic moisture introduced nonnegligible cooling, especially in the irrigated areas.
As a result, verification was performed to quantify the extent of the difference.

5. Verification of modified and control cases

Each simulation started at 0000 UTC (1700 PDT) and simulated 36 h of weather. Thirty simulations were run, for days between 1 July and 15 August 2007; a number of days in July were missing data at 0000 UTC so they were excluded from the sample. The months of July and August were selected to ensure fairly similar weather during the simulation period, and because previous work with MM5 had shown the warm bias to be greatest during these summer months. All verification was accomplished for points encompassed by the inner model domain, where the grid spacing was 5 km × 5 km.

Verification was performed separately against two sets of surface observations: those in the database of the Air Force Weather Agency (AFWA) and those from the South Coast Air Quality Management District (AQMD). This was done to avoid comparing the forecasts to sets of observations that might have different characteristics. Only results from verification with the AFWA data are reported, because the AQMD stations lacked coverage in the areas of commercial irrigation. Model values were interpolated from the model grid to the locations of the surface stations, to compute differences from the observations. For each dataset, the verification results were averaged over the 30 simulations to develop graphs of the bias and mean absolute error (MAE) as functions of simulation hour. The statistical significance of the differences between the cases of the bias and MAE was determined by the procedure described in the next subsection.

a. Determining the statistical significance of differences in bias and MAE

Let $O_{ijk}$ be the observation of a parameter at simulation day $i$, at location $j$, and at hour $k$. Similarly, let $F^c_{ijk}$ and $F^m_{ijk}$ be the forecast values of the same parameter in simulations for the control and modified cases. Let errors in the forecast control and modified values be denoted by $e^c_{ijk} = F^c_{ijk} - O_{ijk}$ and $e^m_{ijk} = F^m_{ijk} - O_{ijk}$, respectively, and the absolute values of the errors by $a^c_{ijk} = |e^c_{ijk}|$ and $a^m_{ijk} = |e^m_{ijk}|$.

Since the same procedure is followed to evaluate the statistical significance of the differences between the control and modified cases, for both the bias and the MAE,
it is convenient to describe it generally. Let $x_{ijk}$ represent either $a_{ijk}$ or $e_{ijk}$, and similarly for the control case with $x_{cijk}$. Let $n_{ik}$ be the number of observations at simulation day $i$ and hour $k$. Let $\langle \cdot \rangle$ represent the average over all locations of a parameter that depends on simulations hour, location, and day in the set of observations being considered, of which there are several. Thus, for example, for a parameter $\theta$,

$$\langle \theta \rangle = \frac{1}{n_{ik}} \sum_{j=1}^{n_{ik}} \theta_{ijk},$$

Let $\Delta_{ik} = \langle x_{ijk}^m \rangle - \langle x_{cijk} \rangle$. The mean of $\Delta_{ik}$ over the sample of 30 simulation days is

$$\overline{\Delta}_{k} = \frac{1}{30} \sum_{i=1}^{30} \Delta_{ik} = x_{ijk}^m - x_{c}^c,$$

where the overbar represents an average over simulation days. Though the distribution of the $\Delta_{ik}$ is unknown, for the surface parameters considered in this study, a sample of 30 was taken to be large enough for the central limit theorem to apply, implying the distribution is normal.

For a given simulation hour $k$, the time series of $\Delta_{ik}$ is serially correlated. Consequently, in the test to determine whether $\overline{\Delta}_{k}$ is significantly different from zero, and thus whether $\overline{x}_{i}^m$ is different from $\overline{x}_{c}^c$, the variance of $\Delta_{ik}$ over the sample of simulation days must be modified by the factor

$$\frac{1 + \rho_1}{1 - \rho_1},$$

where $\rho_1$ is the lag-one autocorrelation of the series $\Delta_{ik}$ over the simulation days. The null hypothesis is that the population mean of $\Delta_{ik}$ (for fixed $k$) is zero. The sample statistic used to test the null hypothesis is thus

$$z = \frac{\overline{\Delta}_{k}}{\sqrt{V_k(1 + \rho_1)}/30(1 - \rho_1)},$$

where $V_k$ is the variance of $\Delta_{ik}$ over the simulation days (Wilks 2006).

If $|z| > 1.654$, then the null hypothesis is rejected, and the difference in means is significant at the 5% level. On average, at most 1 in 20 identical experiments will yield a $z$ of comparable magnitude.

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**FIG. 7.** As in Fig. 5, but for June.
b. Surface temperature bias and MAE verification over the entire domain

When taken over the entire domain for the 30 days of the study, the hourly verification results show a statistically significant reduction in the forecast temperature bias from the morning through early afternoon. Note that, while the impacts on the model temperature were shown to be much larger on the skin temperature rather than those on the shelter height temperature, the latter are used for verification because that is the parameter available in the surface observation data. Figure 12 shows the bias in temperature compared to AFWA stations, over the entire model domain. The biases of the control case (i.e., without anthropogenic moisture) and the modified case both exhibit strong diurnal variation, and are comparable for most hours except for the morning through early afternoon hours [0400 local time (LT) through 1500 LT]. The difference between the biases is greatest at hour 19 (1200 LT). At that hour, the bias of the control case exceeds that of the modified case by 0.13°C. For hours 26 (1900 LT) and 27 (2000 LT), the magnitude of the bias of the control case is 0.1°C less than that of the modified case. The largest magnitude of the bias, which is negative, occurs at 2000 LT.

It appears that the model cools too rapidly during the evening hours and warms too rapidly during the morning (0600 LT) through early afternoon hours (1400 LT). The addition of anthropogenic moisture slows the rate...
of heating during this time, and slightly accelerates the rate of cooling from late afternoon through 2000 LT. It should be noted that the largest warm bias is only 0.4°C, which is considerably smaller than the 1°–2°C bias observed with previous integrations of the MM5 model over the same domain and similar time periods.

Next, the verification was limited to the areas with anthropogenic moisture in an attempt to isolate the effects of adding the moisture. Calculation of the bias in temperature was restricted to areas with anthropogenic moisture; the results are presented in Fig. 13. Note that the number of observations used in this verification is about half of the number of observations used for verification over the entire domain. The bias of both the control and modified cases again shows strong diurnal variation, and the two are generally comparable except for the period from simulation hour 15 (0800 LT) to hour 22 (1500 LT). During those hours they are as much as 0.2°C apart, which is only slightly larger than for the unrestricted domain comparison. The overly rapid warming seen in the control and modified runs in the morning is not evident over those land types affected by anthropogenic moisture. This may be due to the radiative properties specified for these land-use types.

For shelter temperature MAE verification for the entire domain (Fig. 14), only those hours from late morning to early evening have an MAE for the anthropogenic moisture case that is less than the control case. Though the improvement in MAE during this period, the differences at 1200, 1500, 1700, and 1800 UTC (0500, 0800, 1000, and 1100 LT) are statistically significant. The shelter temperature MAEs, computed for both cases, using AFWA data restricted to those areas where anthropogenic moisture was added, are shown in Fig. 15. As with the verifications over the entire domain, the only time when the MAE for the anthropogenic moisture case is less than the control case is from late morning to early afternoon. Though these differences are small, they are statistically significant. There also is a statistically significant reduction of the MAE in the modified case in the early morning hours (0200–0300 and 1900–2000 LT) of the second day of the forecast period. This reduction may be caused by reduced cooling due to the...
reduction in outgoing longwave radiation that is due to the continued moistening of the lower atmosphere over the inland valleys in the modified case. During the early morning hours of the first day of the forecast, it appears that sufficient moistening of the atmosphere has not occurred to reduce radiative cooling to the levels where this effect predominates over evaporative cooling. This results in higher MAEs for the modified case than the control case during the early morning hours of the first forecast day, but this difference is not statistically significant.

c. Water vapor mixing ratio verification over the entire domain

Verification was performed on the forecast water vapor mixing ratio, using reports from the 31 available AFWA surface stations as truth. AQMD stations do not report variables from which the water vapor mixing ratio may be determined, so no verification was possible with the AQMD station set. Here again, the biases are comparable for the two cases over the entire domain. Taken over all available days and hours, the bias for the control case was $-0.326 \text{ g kg}^{-1}$, while the bias for the modified case was $-0.416 \text{ g kg}^{-1}$. Note that most of the AFWA observations of mixing ratio are made only every 6 h, at the times of major and minor synoptic observations.

d. Surface temperature verification for a station within an irrigated area

The largest anthropogenic moisture amounts occur in commercially irrigated regions. The station at the Bakersfield airfield is located in a region in the Central Valley that is extensively irrigated. Averaged over all days and forecast hours, the control case had a bias of $-1.57^\circ\text{C}$ versus $-2.36^\circ\text{C}$ for the modified case, so the overall effect of the anthropogenic moisture in the modified case was to cool the model atmosphere significantly at this station. Figure 16 shows the bias for the control and anthropogenic moisture cases, as a function of forecast hour, computed for the sample of 30 paired simulations. The addition of anthropogenic moisture all but eliminated the midmorning to early evening temperature warm bias seen in the control run. However, it exacerbated the early morning cold bias. To see if the difference in biases between the cases was statistically significant at the 95% level, the $t$ test was applied, allowing for the possibility that the variances of the biases differed. In this case the appropriate $t$ test is the...
two-tailed test, where the null hypothesis is rejected if the magnitude of the sample \( t \) statistic exceeds a certain value. It was found that the reduction of the late morning to early evening warm bias at Bakersfield is statistically significant, as are the few degradations that occurred in the evening and early morning hours.

Figure 17 shows the shelter temperature MAE for Bakersfield, as a function of time of day and simulation hour. There is a significant reduction in MAE in the modified case, from late morning through early evening, as compared to the control case. The improvement in MAE for the modified case is nearly 40% for a number of these hours. However a significant degradation in skill in the modified case is evident during evening and early morning hours.

The generally negative temperature bias found at Bakersfield in the control case was surprising, and is what led to a reexamination of the case studies that had initially pointed the way to the perception of a positive bias. The original case studies had mixed results: some had a negative bias while others had a positive bias. Adding anthropogenic moisture generally made the atmosphere cooler, so in the present study it reduced the late morning warm bias. It also made any negative bias more negative.

e. Water vapor mixing ratio verification for a station within an irrigated area

Assuming that a portion of the warm bias seen was due to a lack of anthropogenic moisture in the control case, one would expect to see a corresponding dry bias. Figure 18 shows these conditions are seen in the control case, between the hours of 1500 and 1800 LT, when the warm bias is at its peak. However, much of the daytime warm bias in the control case, from the hours of 0900 to 1300 LT, occurs during periods where there is a moist bias. The addition of anthropogenic moisture does lessen the dry bias during the time of the peak warm bias in the model. However, it also significantly (the same statistical significance testing was used for the mixing ratio as was used for temperature) exacerbates the model moist bias that occurs, from the early morning hours through the early afternoon. It terms of the total humidity forecast error as represented by MAE (see Fig. 19), a slight reduction in MAE is seen in the modified case that corresponds to the reduction of the temperature MAE for this case during the 1500–1800 LT period. However, unlike the reduction in the temperature MAE, where the improvement is statistically significant, the same cannot be said for the mixing ratio.

FIG. 16. Shelter temperature bias for control (solid) and anthropogenic moisture (dashed) cases vs forecast hour for Bakersfield. Points with stars indicate that the difference between the two cases was statistically significant at the 95% level.

FIG. 17. Shelter temperature MAE for the control (solid) and anthropogenic moisture (dashed) cases vs simulation hour and time of day for Bakersfield. Statistically significant differences at the 95% level are indicated by a star on the line that has the smaller MAE.

FIG. 18. The 2-m mixing ratio bias for control (solid) and anthropogenic moisture (dashed) cases vs forecast hour for Bakersfield. Points with stars indicate that the difference between the two cases was statistically significant at the 95% level.
6. Summary

Initially it was thought that WRF would show the same 1°–2°C summer daytime warm bias at the surface, as has been seen in MM5 results over southern California, a bias that, it was hypothesized, would be corrected by including the effects of enhanced evaporation due to anthropogenic moisture, especially irrigation. In point of fact it was found that the control case had a relatively modest bias of only 0.2°–0.4°C during the late morning and early afternoon and had a negative bias in the evening and early morning hours.

The skin and surface temperatures of the model, over the irrigated areas, generally exhibited significant cooling in the modified case compared to the control case, while areas of domestic water use showed small or non-existent differences.

Verifications of the modified and control cases, over the entire inner domain, or over only those areas where anthropogenic moisture was added, showed a reduction in the daytime warm bias, and a slight worsening of the nighttime cold bias. Though these reductions were modest, they proved to be statistically significant for many of the forecast hours. The measure of the total shelter temperature error, in terms of MAE for the entire domain, showed some significant reduction of error for a few of the daylight hours, while also showing a significant increase in error for some nighttime hours. However, while the decrease (increase) at some hours could be considered significant, the amount of improvement (degradation) calculated for the entire inner domain was only 1%–2%.

Focusing on one location (Bakersfield) in the vicinity of a large area of commercial irrigation, it was found that anthropogenic moisture significantly reduced the daytime surface temperature bias, and improved the model’s skill at simulating—forecasting the daytime shelter temperature. However, it also significantly worsened the cold bias and decreased skill during the nighttime hours at this location. It only slightly improved the humidity forecasts during the peak of the warm bias, while worsening the moist bias during the morning and early afternoon hours.

Results of this study indicate that anthropogenic moisture is an important source of enthalpy and humidity, and that it should be included in a way similar to the one followed here, at least for areas with natural precipitation comparable to or less than anthropogenic moisture for all or part of the year. The results also suggest that a more accurate representation of other processes affecting surface parameters should be considered.

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FIG. 19. The 2-m mixing ratio MAE for control (solid) and anthropogenic moisture (dashed) cases vs forecast hour for Bakersfield. Statistically significant differences at the 95% level are indicated by a star on the line that has the smaller MAE.

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