Evaluation of the Summertime Low-Level Winds Simulated by MM5 in the Central Valley of California

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ABSTRACT

A season-long set of 5-day simulations between 1200 UTC 1 June and 1200 UTC 30 September 2000 are evaluated using the observations taken during the Central California Ozone Study (CCOS) 2000 experiment. The simulations are carried out using the fifth-generation Pennsylvania State University–NCAR Mesoscale Model (MM5), which is widely used for air-quality simulations and control planning. The evaluation results strongly indicate that the model-simulated low-level winds in California’s Central Valley are biased in speed and direction: the simulated winds tend to have a stronger northwesterly component than observed. This bias is related to the difference in the observed and simulated large-scale, upper-level flows. The model simulations also show a bias in the height of the daytime atmospheric boundary layer (ABL), particularly in the northern and southern Central Valley. There is evidence to suggest that this bias in the daytime ABL height is not only associated with the large-scale, upper-level bias but also linked to apparent differences in the surface forcing.

1. Introduction

One of the major factors contributing to errors in air pollution simulations and forecasts is the accuracy of the meteorological fields that drive the simulations. Typically, these meteorological fields have been derived from numerical weather prediction (NWP) models. While there have been improvements to NWP models in recent years, especially with the advance of computing power that allows for the use of very high resolution simulations, more evaluation of these models has been needed to further improve their accuracy. Over the past few decades, increasingly more three-dimensional meteorological observations for air-quality studies have been accumulated for model evaluation through various field campaigns. However, most of the observations were made in the lowest 2–3 km above the surface, with the assumption that the model-simulated, upper-level, large-scale meteorological conditions are accurate enough. The prevailing thought was that errors in the parameterizations used to represent physical processes in the atmospheric boundary layer were the primary reason for the inaccurate low-level wind simulations. Furthermore, the common practice in model evaluation has been to focus on a few high-impact cases instead of a long-term persistent evaluation. This practice was justifiable given the fact that the aforementioned field campaigns barely lasted for an entire summer.

One of the fundamental aspects of model evaluation is to characterize the seasonal behavior of the model in particular applications so that statistical significance can be assigned to the evaluation results. As a community mesoscale model, the fifth-generation Pennsylvania State University–National Center for Atmospheric Research (NCAR) Mesoscale Model (MM5; Grell et al. 1995) has long been used in the Central Valley (CV) of California to simulate low-level winds and temperature for air-quality management and forecasting (see Seaman et al. 1995; Stauffer et al. 2000). These studies have investigated the performance of MM5 in simulating the meteorological conditions of poor-air-quality events in the CV by focusing on individual case studies. There has been no evaluation of the MM5 over the entire summer season for its performance in typical multiday simulations of atmospheric
boundary layer (ABL) winds for air-quality applications in the CV. However, evaluation of the seasonal performance of the MM5 for air-quality applications has been performed in other areas. For example, Zhong et al. (2005) performed an evaluation of MM5 during a warm season for air-quality applications. Their study focused on a statistical comparison between the model forecasts and observations in the Great Lakes area where, unlike the CV, the terrain is not very complex. The seasonal performance of the MM5 has also been evaluated in mesoscale forecast applications. For example, Mass et al. (2002) and Colle et al. (2000) investigated how the refinement of the model resolution and the synoptic-scale predictability affect mesoscale predictability. Their investigations focused on the verification of forecasted surface parameters, such as precipitation, in a cool season in the complex terrain of the Pacific Northwest. This study is different from the previous evaluations of the performance of MM5 in that it focuses on the evaluation of the low-level flow patterns in the CV, an area surrounded by complex terrain, during a warm season when the synoptic-scale forcing is typically much weaker than that associated with precipitation events.

Over the past few years, improvements in the observing systems, data assimilation, and numerical models, coupled with advancements in air-chemistry modeling, have led to operational forecasting of air quality in the United States. It is foreseeable that capabilities of local high-resolution prediction by local authorities using well-established NWP models, such as MM5, will grow rapidly over the next decade for a number of valuable new services and management strategies. Although results from model evaluation based on a single case study no doubt provide useful information on the model’s performance and how to improve it, such information lacks statistical significance because of the nature of single-case studies. Therefore, it is an important step in a model evaluation process to include season-long evaluation of a mesoscale weather prediction model to provide statistically meaningful information on the model’s performance. Additionally, the large Central California Ozone Study (CCOS) dataset provides a unique opportunity to evaluate MM5’s performance in simulating the low-level flows within the CV of California during an entire summer season.

In this study, a season-long set of 5-day simulations between 1200 UTC 1 June and 1200 UTC 30 September 2000 is evaluated using the CCOS observations. The paper is organized as follows: in the next two sections, the model configuration is explained and the observations used for the simulation evaluation are described; section 4 presents the evaluation results; and discussions and conclusions are provided in section 5.

2. Model configuration

In this study, version 3 of MM5 (Grell et al. 1995) is used to perform a series of 5-day simulations (except for two 3-day periods at the beginning and end of the time period) starting 1200 UTC 1 June 2000 and ending 1200 UTC 30 September 2000 and centered around the 5-day intensive observation period (IOP) that began 29 July 2000 and ended 3 August 2000. The MM5 simulations for this study are run using a set of 36–12–4-km one-way nested grids (see Fig. 1) that have 50 vertical stretched levels, 30 of which are within the lowest 2 km, with the lowest model level at about 12 m above the surface. The grid configuration is the result of a consensus among the CCOS project participants and is based on the tradeoff between available computing resources limiting the domain size and acceptable accuracy of the model forecasts/simulations. Similar grid configurations have been widely used by local air-quality modelers for evaluating the performance of atmospheric chemistry models (see, e.g., Ling et al. 2010). The boundary and initial conditions for the simulations in this study are prescribed using the 6-hourly 40-km National Centers for Environmental Prediction (NCEP) Eta analyses. The 10-min U.S. Geological Survey (USGS) topographic data are used for the 36-km grid, the 5-min data for the 12-km grid, and the 2-min terrain resolution for the 4-km grid. All of the simulations use the Eta atmospheric boundary layer scheme (Janjić 2002). The Noah land surface model is used for simulating the changes of surface soil conditions. The Dudhia simple microphysics parameterization is used along with the Dudhia shortwave and Rapid
Radiation Transfer Model (RRTM) longwave radiation parameterization schemes. The 36- and 12-km grids use the Grell convective parameterization scheme (Grell 1993), whereas no convective parameterization scheme is used on the 4-km grid. Details of all these physics options are available in Grell et al. (1995) and the latest MM5 Users’ Guide (available online at http://www.mmm.ucar.edu/mm5/documents/tutorial-v3-notes-pdf/mm5.pdf). Since the simulations are initialized using the NCEP Eta analysis, the NCEP North American Regional Reanalysis (NARR; Mesinger et al. 2006) is used as a different and better analysis to compare with the simulated large-scale, upper-level flows.

3. Data used for evaluation

During the CCOS 2000 field experiment, a network of twenty-four 915-MHz wind profilers and one 449-MHz wind profiler were deployed to collect information on the winds and temperature in the lower troposphere in the CV for the purpose of improving the understanding of the role of meteorological conditions in the transport of air pollutants and their precursors. The overall objective of the CCOS 2000 field experiment is to improve the air-quality modeling system that is currently used in preparing plans to attain the new federal 8-h maximum ozone standard that has recently increased to 85 ppbv, as well as to update the Clean Air Plan to attain the California state ozone standard. The data collected from the wind profiler sites, along with the surface data at these sites, are used in this study to evaluate the performance of MM5. The wind profilers provide not only hourly averages of wind speed and direction, typically to heights of about 3000 m AGL, but also virtual temperature up to about 1500 m AGL using the radio acoustic sounding system (RASS) technique. The information collected by the wind profilers can also be used to determine the depth of the daytime convective ABL by visually inspecting values of range-corrected signal-to-noise ratio (SNR); vertical velocity, which is large within the convective ABL; and radar spectral width, which is a measure of turbulence intensity (White 1993; Angevine et al. 1994; Bianco and Wilczak 2002).

4. Results

The flow patterns at a given time in the CV can vary from one part of the valley to another. The flow pattern observed during the 5-day period of 29 July–2 August 2000 was typical of the summertime flow regime (Bao et al. 2008) in the CV that is associated with poor air quality. In the Sacramento Valley (SV), the flow was characterized by the daily reversal of up- and down-valley flows, the diurnal reversal of up-slope and down-slope flows along the mountains, and the formation of the Shultz eddy. In the northern San Joaquin Valley (SJV) and southern SV (i.e., the central part of the CV), the flow regime is characterized by the incoming flow through the Carquinez Strait that splits into flows up the SV and SJV. In the southern SJV, the flow is characterized by the acceleration of the incoming flow up the valley at night forming a nocturnal low-level jet, the up-slope and down-slope flows along the mountains, and the formation of the Fresno eddy. Since these three parts of the CV typically have very different flow patterns, the performance of MM5 is evaluated in these three different parts of the CV.

a. Areal comparison of winds over the entire summer

The first step in evaluating the overall performance of MM5 during the summer involves examining the errors with respect to different locations within the CV. To do this evaluation, the CV is divided into three areas: the SV, the central part of the CV, and the SJV. Three areal clusters of profiler locations are used to evaluate the model performance in each of these regions. These clusters are referred respectively as the Sacramento cluster, the Central cluster, and the Fresno cluster (see Fig. 2). The wind-profiler sites that are included in the averaging in the Sacramento cluster (see Fig. 2) are Redding (RDG), Chico (CCO), Arbuckle (ABK), and Pleasant Grove (PSG). The profiler sites included in the Central cluster are Livermore (LVR), Los Banos (LBA), Waterford (WFD), Tracy (TCY), Stevinson (SVS), and Sacramento (SAC). The profiler sites included in the Fresno cluster are Fresno (FAT), Lemoore (LEM), Lost Hills (LHS), Angiola (AGO), Bakersfield (BKF), and Visalia (SJV). The average difference in elevations of all the sites in an individual cluster is less than 40 m, and thus the effect of topographic variation on the averaged properties of each cluster is negligible.

Figure 3 compares the diurnal cycle of the profiler-observed and simulated $u$ and $v$ components of the wind rotated counterclockwise $29^\circ$ so that the $u$ component represents the across-valley flow and the $v$ component represents the along-valley flow and the wind speed averaged over the entire summer period for each areal cluster. In the Sacramento cluster, there is less across-valley flow in the observations from the northeast (i.e., the negative across-valley component) during the night and early morning (300–1800 UTC) than in the MM5.
FIG. 2. Locations of profiler sites and surface sites that are included in the three clusters used to evaluate the MM5 simulations. The profiler sites are labeled by their three-letter identity codes. Surface sites are colored dots. The Sacramento cluster is labeled in red, the Central cluster in green, and the Fresno cluster in blue.

simulations (see the upper panels of Figs. 3a and 3b). It is clearly evident that the westerly across-valley flow is stronger between 200 and 600 m in the MM5 simulations than in the observations in the Central cluster (middle panels, Figs. 3a,b). This indicates that the incoming flow is stronger in the model than observed.

Because of the law of mass conservation, this stronger westerly across-valley flow is closely associated with the stronger simulated nocturnal low-level jet in the SJV. However, at around 1000 m AGL and from 0400 to 1200 UTC and from 1500 to 1600 UTC, the observed across-valley winds in the Central cluster have an average westerly component, while the simulated winds have an average weak easterly component (middle panels, Figs. 3a,b). For the Fresno cluster, there are more layers where the wind has a negative across-valley component in the observations than in the simulations and the observed and simulated layer in which there is diurnal transition from the positive to negative component is different, particularly in the lowest 800 m AGL. Furthermore, the observed across-valley flow in the Fresno cluster shows a diurnal change in sign associated with the alternation of local downslope–upslope flows, while the diurnal signal in the simulated winds is relatively weaker (i.e., the sign change in the simulated winds does not extend as far toward the ground as in the observed winds and is more elevated than the observed winds).

Figure 3 also shows the comparisons of the observed and simulated along-valley flow averaged over the three areal clusters. It can be seen that during the late afternoon and most of the night (2200–1200 UTC), the observed winds in the SV are up-valley, while during the morning and early afternoon, the winds are down-valley (Fig. 3c, top). However, the MM5-simulated along-valley winds averaged over the Sacramento cluster (Fig. 3d, top) are only up-valley from 2200 to 0400 UTC. During the rest of the day, the simulated along-valley winds in the SV are down-valley, meaning that the MM5-simulated along-valley winds turn down-valley much earlier than observed. The up-valley flow in the Central cluster in the MM5 simulation (Fig. 3d, middle) is faster and deeper than observed (Fig. 3c, middle), while the up-valley flow at night averaged over the Fresno cluster, which is the low-level jet, is stronger and deeper in the MM5 simulations than observed (Figs. 3c,d, bottom), as also seen in the Central cluster.

The discrepancies between the observed and simulated wind speed in all three clusters are readily apparent in Figs. 3e and 3f. To better quantify these differences, the bias of the wind speed is calculated for each cluster (Fig. 4). In the Sacramento cluster, the MM5-simulated winds are faster than the observed winds by about 1–2 m s$^{-1}$ almost the entire day below about 600 m AGL. Above 600 m AGL, the MM5-simulated winds are slower than observed by about 1–3 m s$^{-1}$. In the central cluster, the low-level (below about 1000 m) MM5-simulated wind speed is mostly greater than observed by about 1–3 m s$^{-1}$, while aloft, the MM5-simulated wind speed is less than observed by about 1–2 m s$^{-1}$ (middle panel of Fig. 4a). The bias of the wind speed in the Fresno cluster indicates that the MM5-simulated low-level jet is faster than observed by the profilers by about 3–4 m s$^{-1}$ (bottom panel of Fig. 4a). The RMSE of the wind speed (Fig. 4b) indicates that overall, the errors in the low-level wind speed below 2000 m are the greatest in the Sacramento cluster and the least in the Fresno cluster. Additionally, relatively greater RMSEs are seen in the wind speed above 1500 AGL. At night, the RMSEs in the Fresno cluster at low levels are greater than the other two clusters, confirming again that there are errors in the low-level jet.

An interesting comparison of the observed and simulated winds corresponding to the three clusters is in terms of 4-month averaged diurnal directional variance as seen in Fig. 5.2 The simulated winds averaged over the Sacramento cluster show more directional variance than the observed winds from late afternoon at ~2100 UTC to early morning at ~1200 UTC and less during the

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2 Here the measure of the 4-month directional variation at a given time in the diurnal cycle is defined as $\sqrt{\frac{\sum (u_i)^2 + (v_i)^2}{\sum (u_i)^2 + (v_i)^2}}$, where $u_i$ and $v_i$ are the two orthogonal components of the wind vector at day $i$. 
FIG. 3. Time–height series of the seasonally averaged diurnal cycle of the (left) profiler-observed and (right) MM5-simulated (a),(b) across-valley component of the wind, (c),(d) along-valley component of the wind, and (e),(f) wind speed for the Sacramento, Central, and Fresno clusters. Height is in meters above the ground.
daytime (from 1200 to 2000 UTC) at lower levels (below 1400 m AGL). The simulated winds overall have more directional variance than the observed winds at upper levels. The directional variance of the simulated winds in the Central cluster is similar overall to that observed at lower levels but greater than the observed winds at levels above 1200 m AGL, while in the Fresno cluster the directional variance of the simulated winds is overall less than the observed winds. Further, the directional variances in the Central and Fresno clusters show an obvious diurnal trend in both observed and simulated winds.

The comparison of the directional variance also reveals some differences in the directional persistence between the observed and simulated winds. Overall, the simulated daytime winds show a layer of persistent direction (i.e., less variance) that is deeper than the observed winds in the Fresno cluster, whereas in the Sacramento cluster the
direction of the simulated nocturnal winds is less persistent (i.e., with more variance) than the observed winds, particularly near the surface. The deeper layer of persistent direction in the Fresno cluster may also be associated with more vertical mixing of the momentum associated with the horizontal winds than that observed in the SJV. Evidence to support the notion that the simulated momentum associated with horizontal winds tends to be mixed more in the vertical direction will be discussed in section 4c.

Figure 6 shows a time–height series of the diurnal cycle of MM5-simulated and wind-profiler winds averaged over the entire summertime period in the three areal clusters (the Sacramento, Central, and Fresno clusters). It is clear that the errors in the wind direction are greatest in the Sacramento cluster and are least in the Fresno cluster. In the Sacramento cluster, the MM5-simulated winds aloft are more westerly, while the observed-profiler winds are more southwesterly. The comparison of the nighttime winds averaged over the Central cluster between 200 and 1000 m shows that the MM5-simulated low-level jet is stronger than observed, which is consistent with the differences between the simulated and observed winds shown in Figs. 3c–f. Additionally, the MM5-simulated winds between 600 and 1800 m from 0000 to 0600 UTC have more of a northwesterly component than the observed winds. Of all the three clusters, the MM5-simulated winds in the Fresno cluster are in the best agreement with the profiler-observed winds at all levels and times. The greatest differences in the Fresno cluster occur during the night, where the low-level jet, which is present between 0000 and 0800 UTC and below about 1000 m, is too strong in the MM5 simulations. Figure 6 also shows that the winds within
the daytime ABL are simulated well, better than any other time during the day and at any other height, in both the Central and Fresno clusters. This good agreement of the winds in the ABL indicates that the mixing within the daytime ABL is simulated well in the SJV. However, discrepancies between the simulation and the observations can be discerned in Fig. 6. Particularly, the simulated and observed wind directions within the ABL in the Sacramento cluster are noticeably different, and the depth of the simulated ABL is larger than observed in all three clusters. Further discussion of the reasons for the differences between the observed and simulated atmospheric boundary layers is presented in section 4c.

Figure 7 depicts the comparison of the observed and simulated along-valley winds averaged over the lowest 500 m AGL in each cluster. In the Sacramento cluster, the profiler-observed winds turn up-valley during the afternoon. The up-valley flow is maintained throughout most of the day and is strongest around sunset (0300 UTC). The MM5-simulated winds, however, are more cross-valley than up-valley and are much weaker than the observed winds. The comparison of the winds averaged over the lowest 500 m AGL in the Central and Fresno clusters again indicates that MM5 has a stronger low-level jet than the wind-profiler observations in the SJV (see the middle and bottom panels in Fig. 7) than observed. These characteristics in the differences of wind directions suggest that there are significant differences in the large-scale setting and surface forcing between the MM5 simulations and observations since the intensity and direction of the marine airflow through the area of the Central cluster is driven by the large-scale pressure gradient and the land–sea thermal contrast [see relevant discussions in Michelson and Bao (2008)].

Figure 8 shows the hodographs averaged over the sites in each cluster from 100 to 500 m above the ground. The biggest differences between the observed and MM5-simulated hodographs are in the Sacramento cluster. Although both the observed and the MM5-simulated hodographs in the Sacramento cluster undergo a similar diurnal cycle (changing from counterclockwise rotation to clockwise rotation and back to counterclockwise rotation), MM5 has a bias in the background flow, as indicated by the differences in the center of the hodographs. For the central cluster, in addition to a fast speed bias, as indicated by the difference between the simulated and observed hodographs, there is also more of an abrupt change from down-valley to up-valley flow in the observations than in the MM5 simulations. In the Fresno cluster, the fast speed bias at night in the MM5-simulated low-level winds is readily apparent. Additionally, although both the observed and simulated hodographs have a variation in the wind vector rotation during the diurnal cycle, there are differences in the variation of rotation, especially during the day (see Fig. 8d). The observed hodograph begins with a clockwise rotation during the day, then changes to a counterclockwise rotation, and then back to a clockwise rotation, while the simulated hodograph starts with a counterclockwise rotation and then changes to a clockwise rotation.

The most important result of the hodograph comparisons is the variation in the wind vector rotation and wind speed in the three clusters. The differences in the rotation of the observed and simulated hodographs can be explained by the errors in the simulated large-scale pressure gradient, large-scale flow, and local topographically induced pressure perturbation. In general, as indicated by Kusuda and Alpert (1983) [see also relevant discussions in Bao et al. (2005, 2008)], the imbalance between the local topographically induced pressure perturbation and the background pressure gradient is responsible for the lack of the clockwise (in the Northern Hemisphere) wind rotation or for the counterclockwise wind rotation in locations with significant complex topography and surface thermal contrast (such as in parts of the CV). It is also reasonable to assume that a similar imbalance in pressure forcing can also be responsible for an abrupt change, rather than gradual rotation of wind direction. All the differences shown in Fig. 8 indicate that the simulated imbalance between the local topographically
induced pressure perturbation and the background, large-scale pressure gradient are significantly different from the actual imbalance, as depicted by the hodographs of the observed winds.

Figure 9 shows the seasonally averaged diurnal cycle of the observed and simulated surface winds at the surface sites shown in Fig. 2. As is true for the winds averaged over the lowest 500 m, the largest differences...
between the observed winds and the MM5-simulated winds occur in the Sacramento cluster, and the smallest differences occur in the Central cluster. The differences are greater at the surface in the Fresno cluster than they are averaged over the lowest 500 m (comparing Figs. 7 and 9). As seen in Fig. 7, in the Central and Fresno clusters, the MM5-simulated winds are too strong. Additionally, MM5 has a difficult time simulating the up-valley flow in the SV, and the MM5-simulated winds in the Sacramento cluster are weaker than observed. However, it is obvious by comparing the upper panels of Fig. 9 with Fig. 7 that the simulated duration of the up-valley flow in the SV is better at the surface than aloft. There is a direction bias in the Fresno cluster, especially in the evening and into the night, which suggests a bias in the intensity of the up-valley flow during the day and the nocturnal low-level jet during the night.

b. Connection of the errors in the low-level winds to the errors in the upper-level forcing

The differences between the MM5-simulated winds and profiler-observed winds seen in Figs. 3–9 can be partially explained by examining the differences in the upper-level patterns. As shown in Fig. 8, for instance, the displacement of the center of the simulated hodograph from the center of the observed hodograph is a direct indication of the large-scale influence on the low-level valley-scale winds. As discussed in Bao et al. (2008), the low-level winds in the CV are dominated by the incoming flow associated with the marine air intrusion from the San Francisco Bay area. Since this incoming flow is driven by the thermal contrast between the CV and the offshore sea surface temperature, the dynamical explanation provided by Estoque (1962) on the impact of the large-scale pressure gradient on the intensity of locally thermal-driven flow can be used to understand how the upper-level, large-scale flow contributes to the errors in the low-level winds in the CV. The displacement of the hodograph center is controlled by the low-level, large-scale pressure gradient. Since this gradient is strongly affected by the upper-level pressure gradient, the errors in the large-scale upper-level pressure gradient and winds are directly responsible for the displacement of the simulated hodograph centers relative to the observations. Therefore, the displacement between the observed and simulated hodographs indicates that there are errors in the simulated large-scale forcing.

Figure 10 shows differences in the 500-hPa geopotential height patterns averaged over the entire period at 1200 UTC from the North American Regional Reanalysis and the 36-km grid of MM5. The upper-level high is positioned closer to the Four Corners area in NARR, whereas in MM5 the high is farther to the southeast. Furthermore, the trough axis is farther east (closer to the coast in northern California) in the MM5 simulations than in NARR. These differences result in the MM5-simulated upper-level flow being more west-northwesterly aloft in northern California, whereas the observed flow is more southwesterly, as seen in the winds aloft in the Sacramento and Central clusters in Fig. 6. One way to quantify the differences in the observed and simulated low-level winds is to compare the geopotential gradient over the CV. Figure 11 shows the difference between the observed and simulated geopotential gradient in the SJV (represented by the solid vector resultant from the geopotential differences of Oakland–Reno and Oakland–Vandenberg) as well as in the SV (represented by the dashed vector resulting from the geopotential difference of Oakland–Redding and Oakland–Reno) for both the NARR (black vectors) and the MM5 36-km simulations (red vectors). The directions of the observed and simulated geopotential gradient are different, with the simulated winds tending to have a northerly bias. Additionally, the sizes of the simulated geopotential gradient in both the SJV and the SV are greater than observed. Since the large-scale winds at 500 hPa in this region are mostly geostrophic and thus are approximately perpendicular to the geopotential gradient vector, the vector differences shown in Fig. 11 indicate that the simulated winds at 500 hPa tend to have a stronger northerly component than observed. This is consistent with the northerly bias in the simulated low-level winds shown in Figs. 7 and 9, as well as with the simulated hodographs having greater
enclosed area than observed, as shown in Fig. 8. Although it is beyond the scope of this paper to identify the actual sources of the errors in the large-scale, upper-level flows, it is worth mentioning that the resolution of the MM5 terrain is not compatible with the upstream flow controlled by the analysis that is based on a model with terrain of a coarser resolution. A consequence of this may be that the large-scale blocking effect of the Sierra Mountains is not correct in the MM5 simulations.

It is also worth pointing out that the differences in the error characteristics of the simulated winds in the northern CV and those in the southern CV, as depicted in Figs. 3–9, are related to the average summertime flow patterns in the northern and southern CV. During the summer, the average flow patterns in the CV are dominated by the northward and southward up-valley flows of the marine air intrusion through the San Francisco Bay area due to the blocking by the Sierra Mountains. As discussed in detail with a case study in Michelson and Bao (2008), there are at least two possible factors for the different error characteristics of the simulated winds in the northern and southern CV. First, the distributions of the winds in the northern and the southern CV are not symmetric. Most of the incoming marine flow through the San Francisco Bay area veers into the southern CV and hence the winds there are more strongly influenced by the land–sea thermal contrast than the winds in the northern CV. Second, as depicted in Fig. 10, the northern CV is closer to the relatively stronger upper-level forcing associated with the upper-level trough offshore of California than the southern CV, while the southern CV is closer to the relatively weaker upper-level forcing associated with the subtropical high. In other words, because the large-scale patterns differ over the CV, the error distribution also varies. The average 500-hPa geopotential gradients in both the northern and southern CV (Fig. 11) indicate that the upper-level large-scale forcing influences the low-level winds in the CV in such a way that it impedes

![Fig. 10. The 500-hPa geopotential height (color contours) at 1200 UTC averaged over the entire 1 Jun–30 Sep time period, from (top) NARR and (bottom) MM5 at 36-km grid resolution.](image)

![Fig. 11. The resultant gradient of the 500-hPa geopotential height between Oakland–Reno and Oakland–Vandenberg. The observed and simulated 500-hPa geopotential gradient in the San Joaquin (SJV; solid vector) as well as in the Sacramento Valley (SV; dashed vector) for both the NARR (black vectors) and the MM5 36-km simulations (red vectors).](image)
the up-valley flow in the northern CV, whereas it enhances the up-valley flow in the southern CV. Since the magnitudes of the average simulated 500-hPa geopotential gradients are greater than those in NARR, it is no surprise that in the northern CV the simulated up-valley flow becomes weaker than the observed flow, while in the southern CV the simulated up-valley flow is overall stronger than the observed flow. Thus, the differences in the upper-level, large-scale forcing shown in Figs. 10 and 11 have a significant bearing on the error distributions of the model-simulated low-level winds.

c. ABL height comparison and its implications

Figure 6 shows not only the comparison of the low-level winds, but also the depth of the daytime ABL. The simulated daytime ABL height is diagnosed from the profile of simulated turbulent kinetic energy (TKE). It is defined as the elevation above the maximum simulated TKE at which the simulated TKE reaches its background value. This definition of the simulated ABL height is consistent with the assumption used to determine the observed ABL height based on the vertical distribution of the signal-to-noise ratio of the wind profiler measurements (see, e.g., Bianco and Wilczak 2002). Figure 6 clearly indicates that the greatest differences between the observed and simulated ABL depth occur in the Sacramento cluster and the smallest differences occur in the Central cluster. In all three clusters, the MM5-simulated ABL depth is shallower than observed in the early morning and late afternoon and deeper than observed at the peak of the daytime ABL development, although the differences at the peak in the Central cluster are small. There are two possible reasons for the characteristics of the errors in the development of the simulated ABL depth. First, as strongly suggested by the differences between the NARR and the MM5-simulated upper-level patterns, the strength of the subsidence over California in the simulation is different from that associated with the analysis. In particular, the subsidence in the MM5 simulations is weaker overall than the analysis because the 500-hPa large-scale high is farther to the southeast in MM5 than in NARR (see Fig. 10); thus, in the simulation the CV is less directly under the upper-level high than in reality. This weaker subsidence allows the ABL to grow deeper in the simulations. The weaker subsidence in the simulations may also suggest that the recirculation from upslope flows is stronger in the observations than in the simulations. Second, the Bowen ratio (defined as the ratio of the surface sensible heat flux to the latent heat flux) could be greater in the MM5 simulations. This is suggested by the fact that, as shown in Fig. 12, the simulated low-level temperature has a larger diurnal cycle than observed.

The bias, RMSE, and correlation of the MM5-simulated virtual temperature relative to the RASS observations are shown in Fig. 13 for the three clusters. Overall, the MM5-simulated low-level virtual temperature is about 2°–4°C colder than observed during the night and about 1°C too warm in the lowest 200 m during the day (Fig. 13a). This
A larger simulated diurnal cycle of temperature is also seen in the surface 2-m temperature comparisons shown in Fig. 14. This difference in the Bowen ratio could account for the simulated ABL being shallower than observed in the early morning and late afternoon, but deeper than observed at the peak of the ABL development. The RMSE of the temperature also indicates that there are more errors in the temperature at night than during the day in all three clusters (Fig. 13b), which is consistent with the bias. The RMSE is the largest in the Sacramento cluster during the night and the smallest in the Fresno cluster during the day. The simulated and the observed virtual temperatures are better correlated (Fig. 13c) aloft than at low levels and better correlated during the day in all three clusters. Overall, the simulated and observed temperatures correlate the best in the Fresno cluster.

The overall cooler, simulated ABL may be attributed to cooler ground surface temperature (possibly associated with an overestimate of clouds) and stronger vertical mixing in the simulation, while the higher Bowen ratio in the simulation may be attributed to an underestimate of the surface soil moisture at the initial time of each simulation. Figure 15 shows that the differences between the observed and simulated solar radiation are small in both the Sacramento and Fresno clusters, but relatively greater in the Central cluster. Since the results

![Figure 13](https://example.com/fig13.png)
shown in Fig. 15 exclude the possibility of an overestimate in the simulated clouds, the underestimation of the initial surface soil temperature and moisture and stronger simulated vertical mixing must be the primary reasons for the characteristics of the errors in the simulated ABL depth shown in Fig. 6. Unfortunately, there are no data available to allow further differentiation between the contributions of the errors in the model’s vertical mixing and soil moisture.

The results from the comparisons of the observed and simulated ABL depth have two implications. First, the large-scale biases in the model simulation, such as those in the subsidence associated with the subtropical high, may have as significant an influence on the accuracy of the simulation of the ABL development as the biases in the direct forcing (such as solar radiation and the surface sensible and latent heat fluxes) of the ABL. Second, since the specification of the soil state and the surface turbulent fluxes are important for an accurate simulation of the ABL evolution, which is critical to air-quality modeling, observations of soil conditions and the surface fluxes are absolutely necessary for the determination of model error.

5. Summary and discussion

Three conclusions can be drawn from this evaluation of season-long, 5-day simulations of the MM5 in California’s CV using observations taken during the Central California Ozone Study 2000 experiment. The first conclusion is that the accuracy of the simulated low-level winds varies in the CV. Overall, the simulated low-level winds are more accurate in the southern part of the valley than in the northern. There are notable biases in the simulated wind speed and direction. The northwesterly component is stronger in the simulated winds than the observed. These biases are consistent with the biases in the observed and simulated large-scale, upper-level flows, indicating that the errors in the simulated upper-level winds and forcing are a major source of the errors in the simulated low-level winds. The second conclusion is that the simulated depths of the daytime ABL have a positive bias, particularly in the northern and southern CV. Examination of the bias with the CCOS observations strongly suggests that this bias not only is associated with the biases in the simulated large-scale, upper-level flow that are more favorable for weaker midtropospheric subsidence, but is also linked to differences in the surface Bowen ratio, as revealed by the bias in the diurnal cycle of the simulated low-level temperature. The evidence of differences in the surface Bowen ratio leads to the third conclusion: the soil moisture in the model is lower than in reality, reflecting the error in the initial soil conditions. Although the results from this study show that the errors in the MM5-simulated low-level winds are to a great degree associated with the errors in the simulation of the large-scale, upper-level
winds and forcing and land surface conditions such as soil moisture, the results do not suggest anything about the errors in the ABL physics of the model. In fact, the observations taken during CCOS do not provide any information that can be used to directly evaluate the ABL physics of the model. To do so, future field experiments in this region are needed to collect surface turbulent fluxes along with soil properties (including soil type, temperature, and moisture).

The results from the study provide an example of how the errors in the MM5-simulated low-level winds in the CV are determined by the errors in both the local dynamic forcing at the surface and the large-scale, upper-level forcing. It has been well known that a major source of errors in regional NWP models is the lateral boundary conditions (Warner et al. 1997) because they control the large-scale setting of the simulated phenomena. As pointed out in a case study by Michelson and Bao (2008), the large-scale contribution to the errors in the simulation of the low-level winds in the CV can be greater than the contribution from the errors in the dynamic forcing at the surface. The results from this study also support the notion advocated in Warner et al. (1997) that careful attention is required in the practice of specifying the large-scale inflows, as provided by the lateral boundary conditions. The accuracy of the lateral boundary conditions is strongly affected by the sizes of the simulation domain and what analysis fields and formulations are used to specify the lateral boundary conditions.

The results discussed above focus only on the influences of the large-scale, upper-level forcing and the local land surface conditions on the MM5 simulated low-level winds in the CV. This does not mean that there are not other factors that contribute to the errors in the simulated low-level winds in the CV. Unfortunately, we do not have reliable observations or analysis to validate all these factors in this study. Also, despite the fact that the results from this study link the errors seen in the low-level winds from a set of MM5 simulations to the errors in the simulated large-scale, upper-level forcing and local land surface conditions, there remain open questions for future studies. One of these questions is: How does one “optimize” MM5 simulations of the low-level winds in the CV? There are many possible ways to reduce the errors in the MM5 simulations based on the results from this study (such as initializing MM5 with a rapid update cycle and running each simulation for no longer than 24 h). However, it has been known that relative to other parts of the United States, large-scale aspects of weather forecasts for the U.S. west coast can be negatively impacted by the insufficient upper-level observations upstream over the Pacific Ocean. The dependence of the simulated low-level winds in the CV on the simulated large-scale, upper-level forcing, as revealed in this study, suggests that there may not be a viable deterministic approach to reduce all the errors reflected in the model–observation discrepancies, especially given the fact that one can only do so much to improve the quantitative accuracy of the model’s initialization and physics. On the other hand, it has been recognized in the numerical weather prediction community that the statistical ensemble approach for probabilistic forecasts/simulations is an effective way to quantify the errors in the model forecasts/simulations. It is our belief that advancing computational capabilities will allow for the use of the ensemble approach to help improve the simulation of the low-level winds in the CV.

REFERENCES

Michelson, S. A., and J.-W. Bao, 2008: Sensitivity of low-level winds simulated by the WRF model in California’s Central


