Sensitivity of Low-Level Winds Simulated by the WRF Model in California’s Central Valley to Uncertainties in the Large-Scale Forcing and Soil Initialization

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ABSTRACT

The sensitivity of the Weather and Research Forecasting (WRF) model-simulated low-level winds in the Central Valley (CV) of California to uncertainties in the atmospheric forcing and soil initialization is investigated using scatter diagrams for a 5-day period in which meteorological conditions are typical of those associated with poor-air-quality events during the summer in the CV. It is assumed that these uncertainties can be approximated by two independent operational analyses. First, the sensitivity is illustrated using scatter diagrams and is measured in terms of the linear regression of the output from two simulations that differ in either the atmospheric forcing or the soil initialization. The spatial variation of the sensitivity is then investigated and is linked to the dominant low-level flows within the CV. The results from this case study suggest that the WRF-simulated low-level winds in the northern CV [i.e., the Sacramento Valley (SV)] are more sensitive to the uncertainties in the atmospheric forcing than to those in the soil initialization in the typical weather conditions during the summer that are prone to poor air quality in the CV. The simulated low-level winds in the southernmost part of the San Joaquin Valley (SJV) are more sensitive to the uncertainties in the soil initialization than they are in the SV. In the northern SJV, the simulated low-level winds are overall more sensitive to the uncertainties in the large-scale upper-level atmospheric forcing than to those in the soil initialization. This spatial variation in sensitivity reflects the important roles that the large-scale forcing, specified by the lateral boundary conditions and the local forcing associated with the soil state, play in controlling the low-level winds in the CV.

1. Introduction

Winds within the lowest few hundred meters above the earth’s surface, hereinafter referred to as low-level winds, are the means by which the pollution emitted by anthropogenic activities near the earth’s surface is transported and dispersed. It is still challenging to accurately simulate low-level winds for air quality-related applications (such as air quality prediction and the State Implementation Plans for air quality control) that involve complex topography because of the complicated processes involved in the interaction between the atmosphere and the earth’s surface. Recently, applying the Weather and Research Forecasting (WRF) Model (Skamarock et al. 2005) to air quality problems has become increasingly attractive because of its well-designed mass-conserved numeric schemes and the state-of-the-art land surface model, both of which are essential for the simulation of the mesoscale, orographically forced atmospheric flows. Effort has been taken within the Earth System Research Laboratory (ESRL) of the National Oceanic and Atmospheric Administration (NOAA) to apply the WRF Model to air quality applications in California in order to, in part, assess the skills of the WRF Model in reproducing locally forced meteorological conditions. Successful simulation of these conditions for cases where they can be validated against observations gives confidence that the model can be used to make inferences about meteorological processes described by the model in regions of sparse or no data.

In this study, we examine the sensitivity of the low-level winds simulated by the WRF Model (version
2.1.2) to uncertainties in the atmospheric forcing and soil initialization for a 5-day period in the Central Valley (CV) of California, where many wind profiler and surface observations made during the 2000 Central California Ozone Study (CCOS) field experiment are available for further evaluation of the WRF simulations. Meteorological conditions during the 5-day period are typical of those associated with summertime poor air quality events in the CV. The analysis of both the observations and the WRF simulations (Bao et al. 2008) for this 5-day period has revealed that there are several low-level flow components in the CV: 1) the diurnally oscillating incoming low-level flow associated with the sea breeze through the Carquinez Strait into the Sacramento River delta, 2) the diurnal cycle of up-slope/downslope flows, 3) the up- and down-valley flow in the northern CV, which is hereinafter referred to as the Sacramento Valley (SV), 4) the nocturnal low-level jet in the southern CV, which is hereinafter referred to as the San Joaquin Valley (SJV), and 5) the Fresno and Shultz eddies. Conceptually, the intensity and variation of the incoming flow are controlled by the land–sea thermal contrast directly related to the soil state in the CV and the large-scale forcing (associated with large-scale pressure field). The incoming flow also interacts with the local anabatic–katabatic flows forced by topography, which are in turn subject to the influence of the local soil state and the impact of the incoming flow. Therefore, the low-level winds are not only locally forced, but also strongly affected by the upper-level winds associated with large-scale meteorological conditions. Consequently, the errors in simulated winds on both the large and local scales contribute to the overall errors in the low-level winds in the CV. Assessment of the errors on various scales is a necessary step toward improving the WRF simulations of the low-level winds in the CV. To assess these errors, sensitivity analysis of the low-level winds is performed on a series of three WRF model simulations in which the atmospheric forcing and soil initialization are permuted using two independent operational analyses.

The paper is organized as follows: in the next section, the model configuration is explained and the various sensitivity simulations are described for the case study; section 3 presents the analysis of the results from the sensitivity simulations; and the discussion and conclusions are provided in section 4.

2. Model simulation description

The case chosen for the study is the 29 July–3 August 2000 high-ozone episode, which is one of the poor air quality events that occurred during the CCOS field experiment. The WRF Model, version 2.1.2, is run on three one-way nests at 36-, 12-, and 4-km horizontal grid spacings (see Fig. 1). All meshes use the Eta planetary boundary layer and surface layer schemes, the “Noah” land surface model (LSM), and the Dudhia shortwave and the Rapid Radiation Transfer Model (RRTM) longwave radiation parameterization schemes. The Lin et al. parameterization scheme is used on the 36-, 12-, and 4-km meshes. The Kain–Fritsch convective parameterization scheme is used only on the 36- and 12-km meshes, and no convective parameterization scheme is used on the 4-km mesh. Brief descriptions of the physics parameterization schemes in the WRF Model can be found in Skamarock et al. (2005). There are 50 vertically stretched levels with 30 levels within the lowest 2 km and the lowest model layer is about 24 m thick. The 4-km domain encompasses the CCOS field study area, which extends from the Pacific Ocean in the west to the Sierra Nevada in the east, and from north of Redding, California, south to the Mojave Desert.

First, a WRF simulation is carried out in which the initial and boundary conditions for the 36-km domain are generated using the 6-hourly 40-km National Centers for Environmental Prediction (NCEP) Eta analysis. Then, two additional simulations were performed to investigate the sensitivity of the simulated low-level winds to the uncertainties in the atmospheric forcing and soil initialization by changing the analysis used to initialize the atmosphere and provide the boundary conditions for the 36-km mesh. In one of the two additional simulations, the atmosphere was initialized and the boundary conditions were provided by the Eta
Table 1. Naming conventions for the WRF simulations. The first row and the first column indicate how each simulation is initialized (e.g., in the ETA AIR ECMWF SOIL simulation, the 40-km NCEPEta analysis is used to initialize the atmosphere, while the soil is initialized using the 0.5° ECMWF analysis).

<table>
<thead>
<tr>
<th>ETA</th>
<th>ETCMF</th>
<th>ETA SOIL</th>
<th>ETA AIR ETA SOIL</th>
<th>ECMWF AIR ETA SOIL</th>
<th>ECMWF SOIL</th>
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analysis, while the soil was initialized using the 0.5° European Centre for Medium-Range Weather Forecasts (ECMWF) analysis (see Table 1, hereinafter called ETA AIR ECMWF SOIL). The other additional simulation is the opposite, that is, the ECMWF analysis is used to provide the atmospheric initial and boundary conditions, while the Eta analysis is used for the soil initialization (see Table 1, hereinafter called ECMWF AIR ETA SOIL). All of the simulations were initialized at 1200 UTC 29 July and ran for 120 h, ending at 1200 UTC 3 August 2000 (a period in which meteorological conditions are typically associated with high ozone in the regime).

The synoptic meteorological conditions during the 29 July–3 August 2000 period, as summarized in Bao et al. (2008), are characterized by a ridge at 500 hPa that started to retrogress toward the west from the Four Corners area and strengthen on the first 2 days. The ridge remains strong and continues to slowly move toward the west until 31 July, when it is centered over eastern Nevada. On 1 and 2 August, the ridge axis slowly rotates clockwise moving from southern to northern California. During the same time, a large-scale trough over the eastern Pacific Ocean slowly moves eastward around the northwestern periphery of the high, rendering an increase in the large-scale upper-level pressure gradient. While both the Eta and ECMWF analyses capture the characteristics of the large-scale pattern, they do have discernable differences and it is these differences that are used to approximate the uncertainties in the atmospheric forcing. Examples of the differences between the Eta and ECMWF analyses at the initial time of the simulations of this case are shown in Figs. 2–5. The comparison of 500-hPa winds and geopotential heights from the two analyses at 1200 UTC 29 July 2000 (Figs. 2a,b) shows differences in the mid-troposphere. In particular, the relative positions of the upper-level high over the Great Basin and the westerly trough to the northwest offshore in the ECMWF analysis are slightly different than those in the Eta analysis. Consequently, there is a slightly stronger geopotential gradient (corresponding to a stronger pressure gradient) offshore and over northern California in the ECMWF analysis at 500 hPa. These differences are typical of the uncertainties in the operational upper-level analysis used for regional model initialization. Although the patterns shown in Figs. 2a,b vary slowly over the next 5 days as the position and intensity of the high and westerly trough change, the overall persistent feature (as exemplified by the maps valid at 0000 UTC 1 August 2000 in Figs. 2c,d) in the two analyses during the 5-day period is that the geopotential gradient over the northern CV is greater than that over the southern CV. At 850 hPa, one of the most notable differences is that at 1200 UTC 29 July 2000 the temperature offshore of California is colder in the ECMWF analysis than in the Eta analysis (Fig. 3). Additionally, the differences in the ridge off the Baja California coast causes the winds offshore of the southern half of California to be more shore parallel in the ECMWF analysis than in the Eta analysis. The temperature and moisture in the top soil layer 1200 UTC 29 July 2000 are shown in Figs. 4 and 5 to illustrate the differences in the Eta and ECMWF analysis of the soil state. In the southern SJV, the first layer soil temperature in the ECMWF analysis is colder than the Eta analysis (Fig. 4) and a major difference in the top soil layer is that the CV is moister in the ECMWF analysis than in the Eta analysis (Fig. 5).

Since the WRF model is commonly initialized by one of these two analyses, the differences in the analyzed atmospheric and the soil state depicted in Figs. 2–5 inevitably lead to uncertainties in the WRF-simulated winds. Since the low-level winds in the CV are the result of the interaction between the upper-level flow on the scale of the entire CV and the low-level flows forced locally by the topography and the inhomogeneity of the land surface, it is important to illustrate and eventually measure the relative importance of the sensitivity of the WRF-simulated low-level winds to the uncertainties in the specification of the large-scale atmospheric and local surface conditions that are taken by the WRF Model as input. In this study, it is assumed that these uncertainties can be approximated by the differences between the two analyses, which are widely used to initialize regional weather prediction and research models. It is also assumed that the uncertainties in the soil initialization are more responsible for the errors in the simulated major driving force for the low-level thermally driven flows in the CV than the uncertainties in the atmospheric forcing, while the uncertainties in the atmospheric forcing are more responsible for the errors in the simulated upper-level flow on the scale of the entire CV than the uncertainties in the soil initialization.
3. Results

The low-level flow during the summertime varies with different locations within the CV. Figure 6 presents a conceptual model of the patterns of the low-level winds both during the day (Fig. 6a) and at night (Fig. 6b). These patterns are seen on each day of all the simulations and are based on observed patterns that are present in this case [see Bao et al. (2008) for more details of the observed meteorological patterns of this case] and what are typical for this region during the summertime (see Zhong et al. 2004; Niccum et al. 1995). In particular, there are several distinct flow features within the CV. First, the low-level winds in the SV are characterized by the diurnal variation of the up-valley flow (during the day; Fig. 6a) and the down-valley flow (during the night; Fig. 6b). Second, the central CV is characterized by the splitting of the incoming flow from the San Francisco Bay area (Fig. 6a). Third, the flow in the San Francisco Bay area is characterized by the diurnal variation of the strength of the incoming flow from the Pacific Ocean that moves through the Carquinez Strait. Fourth, the flow in the SJV is characterized by the incoming flow that moves toward the

![Figure 2](image-url)
FIG. 3. The 850-hPa temperatures (color shaded), geopotential heights (solid black contours) and winds valid at 1200 UTC 29 Jul 2000 from (a) Eta initial conditions on the 36-km grid and (b) ECMWF initial conditions on the 36-km grid.
FIG. 4. The first layer soil temperature (K) from (a) the Eta 4-km initialization and (b) the ECMWF 4-km initialization.
FIG. 5. The soil moisture in the first soil layer (m$^3$ m$^{-3}$) for (a) the Eta 4-km initialization and for (b) the ECMWF 4-km initialization.
south, where a low-level jet typically develops at night (Fig. 6b) and interacts with the downslope flows along
the foothills of the eastern side of the SJV to form the
Fresno eddy. In addition to the Fresno eddy, interaction
between the northward inflow and the nocturnal
down-valley flow in the SV often leads to the formation
of a counterclockwise local eddy to the north or north-
west of Sacramento, California, known as the Shultz
eddy during the night (Fig. 6b). The dynamical condi-
tions that are favorable for the formation of both the
Fresno and Shultz eddies are investigated and discussed

In sections 3a, b, scatter diagrams are first used to
illustrate the sensitivity of the low-level winds to
changes in the atmospheric forcing and soil initializa-
tion in different parts of the CV. Then, the spatial varia-
tion of the sensitivity is investigated and linked to the
dominant low-level flows within the CV.

a. Scatter diagrams and sensitivity analysis

Scatter diagrams are chosen among various ap-
proaches to be used along with linear regression to
measure the sensitivity of the low-level winds to atmo-
spheric forcing and soil initialization. In each scatter
diagram, the abscissa is the prognostic variable from
the ETA AIR ETA SOIL, and the ordinate is the coun-
terpart from a simulation in which either the atmo-
spheric forcing is different (ECMWF AIR ETA SOIL
simulation) or the soil initialization is different (ETA
AIR ECMWF SOIL simulation). Each data point in
the scatter diagram corresponds to 1 of the 120 h in the
simulation. As elaborated on by Saltelli et al. (2004), a
scatterplot of a prognostic variable and its perturbed
counterpart can reveal the variance correlation of the
two, and thus provide useful information on the sensi-
tivity of the model output to uncertainties in the model
input. A scatter diagram can also illustrate nonlinear or
possibly other unexpected relationships between the
model input and output, which is helpful in understand-
ing the physical meaning of the results of the sensitivity
analysis.

One popular approach for sensitivity analysis that
has been used in the past by the geosciences community
is the derivative-based approach, in which the so-called
adjoint of the numerical model is required in the com-
putation. This approach is effective, particularly for in-
vestigating which parameter the model is most sensitive
to, and the derivative information has a direct applica-
tion in data assimilation. However, it may not work
adequately in sensitivity analysis if 1) the uncertainties
in the model input are great such that the sensitivities
around significantly different basic states need to be
sampled, 2) the model is highly nonlinear, and 3) the
model’s integration time is long enough so that nonlin-
ear effects in the model become prominent. This is be-
cause the sensitivity results from using the derivative
approach are only informative in the small neighbor-
hood of the basic state where they are computed, and
such results may not provide correct information on the
rest of the uncertainty space of the input parameters. In
contrast, the scatter diagram approach is one of the

![FIG. 6. Conceptualization of (a) the daytime and (b) nighttime low-level wind regimes in California during the five-day episode.](Image)
nondervative approaches that are more suitable for quantitative uncertainty and sensitivity analysis in the presence of uncertainties that are not confined within a small neighborhood of the basic state. Our choice of using the scatter diagram approach is based on the consideration that revealing the sensitivity by examining a limited number of points in the uncertain space is perhaps more informative and robust than computing the derivative approach at a single point in the uncertainty space.

When using the linear regression (Wilks 1995, see his section 6.2) to quantify the sensitivity, the slope parameter \( a \) indicates the linear response of the prognostic variable to the change in either the atmospheric forcing or the soil initialization; the intercept parameter \( b \) measures the overall offset of the prognostic variable from the simulation in which either the atmospheric forcing or the soil initialization is different from the ETA AIR ETA SOIL; and the coefficient of determination \( (R^2) \) provides a measure of the nonlinear response of the prognostic variable to the change in the atmospheric forcing or soil initialization. The linear response to the change in the atmospheric forcing or soil initialization is greater (less) when the slope parameter is farther (closer) from (to) 1. The nonlinear response is greater (smaller) when the coefficient of determination is smaller (greater). Since the sensitivity in question, by definition, the ratio of output increment to input increment measured in the same metric, the mathematical meaning of the linear and nonlinear responses can be interpreted in terms of the Taylor series expansion.\(^1\) That is, the linear response is a measure of the averaged partial sensitivity related to the first-order derivative of the model relative to the input parameters, while the nonlinear response is a measure of the partial sensitivity related to higher-order derivatives. It should be noted that the use of the scatter diagram and the linear regression is not for the purpose of linear fit. Rather, all the numerical aspects of the linear regression should be interpreted as a measure of the sensitivity in question. We also caution that since the analysis is performed for a case study, the quantities revealed in the analysis should be strictly interpreted with respect to the sensitivity to changes in the atmospheric forcing–soil initialization corresponding to the case and is the approximation to the uncertainties in the model initialization.

Since in this study the cross-valley and along-valley directions are important in the interpretation of the sensitivity analysis results in terms of the prominent flow patterns in the CV, both the \( u \) and \( v \) components of the simulated winds are rotated before the sensitivity analysis is performed. The rotated \( u \) component of the wind is perpendicular to the axis of the CV, which is approximately \( 29^\circ \) counterclockwise from the true north, while the rotated \( v \) component of the wind is parallel to the axis of the CV. The positive (negative) rotated \( v \) component indicates the along-valley wind component from south to north (north to south), and the positive (negative) rotated \( u \) component indicates the cross-valley wind component from west to east (east to west). Thus, the rotated \( v \) component represents the up–down-valley flows, while the rotated \( u \) component represents the up–downslope flows along the east and west sides of the CV. Hereafter, unless indicated otherwise, the \( u \) and \( v \) components of the wind refer to the rotated ones (rotated \( 29^\circ \) counterclockwise from the true north). The winds are averaged over the lowest 300 m AGL because the major low-level flow components within the CV for this case are all found below this level.

Scatter diagrams of the \( u \) and \( v \) components averaged over the lowest 300 m AGL for four wind profiler sites (i.e., Bakersfield, Redding, Sacramento, and Livermore, California; see Fig. 7 for the location of the sites) are used to highlight the sensitivity analysis. Figure 8 contains the scatter diagrams for the \( u \) and \( v \) components of the winds averaged over the lowest 300 m AGL at Bakersfield, which is located in the southern SJV (labeled as BKF in Fig. 7). It is shown that the slope parameter associated with the \( u \) component of the wind for the change in the soil initialization (in blue) is farther from 1 (0.54) than that for the change in the atmospheric forcing (in red, 0.73), indicating that the sensitivity to the soil initialization is more than the sensitivity to the atmospheric forcing. For the \( v \) component

\[^1\text{If we denote } X(t_i) = M[X(t_{i-1})] \text{ a prognostic variable at time } t_i \text{ from the control run (where } M \text{ is the model function and } i = 1, 2, \ldots, N \text{ with the initial state } X(t_{i-1}), \text{ and } X_p(t_i) \text{ the counterpart from the perturbed run with the initial state } X_p(t_{i-1}), \text{ the difference between } X_p(t_i) \text{ and } X(t_i) \text{ in theory can be expressed as } X_p(t_i) - X(t_i) = M[X_p(t_{i-1})] - M[X(t_{i-1})]. \text{ Assuming the } M \text{ is differentiable, the application of the Taylor expansion yields } X_p(t_i) = X(t_i) + \partial M/\partial X(t_{i-1})[X_p(t_{i-1}) - X(t_{i-1})] + \text{higher-order terms}, \text{ which leads to the following:} \]

\[
\partial M/\partial X(t_{i-1}) - 1 = \left[ \frac{\partial M}{\partial X(t_{i-1})} \right] - [X(t_i) - X(t_{i-1})] + \text{higher-order terms}/[X_p(t_{i-1}) - X(t_{i-1})].
\]
of the wind, the slope parameter for the change in the soil initialization is closer to 1 (0.68) than that for the change in the atmospheric forcing (0.61), indicating that there is more sensitivity to the change in the atmospheric forcing for the $v$ component of the wind. However, the slope parameters (i.e., the linear response) for the change in the atmospheric forcing and for the change in the soil initialization are more comparable for the $u$ component of the wind than the $v$ component. Furthermore, the slope parameter for the $v$ component of the wind is less than the $u$ component of the wind indicating that at BKF there is more sensitivity to the change in the atmospheric forcing in the $u$ component than in the $u$ component of the wind. The low-level $v$ component of the wind is more influenced by the soil thermal dynamics and the atmospheric dynamics on the scale comparable to the CV than the $u$ component of the wind, which is more influenced by the soil initialization. The nonlinear response of the winds averaged over the lowest 300 m AGL at this particular location, as measured by the size of the coefficient of determination, is stronger for the change in the atmospheric forcing than to the soil initialization. The offset of the simulations (i.e., the intercept parameters), relative to the ETA AIR ETA SOIL, are small enough to be ignored in this discussion. The greater nonlinear response to the atmospheric forcing indicates that at this particular location the forcing associated with the soil initial conditions is more local than the large-scale atmospheric forcing.

The scatter diagrams for winds averaged over the lowest 300 m AGL at Redding, which is located in the CV (labeled as RDG in Fig. 7), are presented in Fig. 9. For both the $u$ and $v$ components of the wind, the slope parameters are closer to 1 for the change in the soil initialization than for the change in the atmospheric forcing (0.94 versus 0.75 for the $u$ component and 0.90 versus 0.72 for the $v$ component), indicating that at Redding, the low-level winds are overall more sensitive to the atmospheric forcing. It is interesting to note that the slope parameters for both the $u$ and $v$ components of the winds averaged over the lowest 300 m AGL are closer to 1 for the change in the soil initialization at Redding than they are at Bakersfield. The nonlinear response at Redding for both the $u$ and $v$ components of the 300-m-AGL-averaged winds is, as at Bakersfield, greater to the change in the atmospheric forcing. Also, the nonlinear response to the change in soil initialization is less at Redding than at Bakersfield; therefore, there is more of a nonlinear response to the soil initialization at Bakersfield than at Redding. All these indicate that at Redding, the 300-m-AGL-averaged winds are less influenced by soil thermal dynamics than at Bakersfield.

The differences of the sensitivity between these two locations may be attributed to several possible factors. First, most of the incoming flow through the San Francisco Bay area veers into the southern CV (i.e., the SJV) and the intensity of the flow is largely controlled by the land–sea thermal contrast, which is most directly impacted by the uncertainties in the soil initialization. Therefore, the SJV is more impacted by the uncertainties in the soil initialization. Second, Bakersfield is farther from the San Francisco Bay area than Redding, thus the part of the incoming flow reaching Bakersfield has more time to be modified by the local land–surface processes than the part reaching Redding. Third, as depicted in Fig. 2, Redding is under a relatively stronger upper-level forcing associated with the upper-level trough offshore of California, while Bakersfield is under relatively weaker upper-level forcing associated with the subtropical high to the east of the CV. Since the uncertainties in the upper-level analysis, as exemplified by Fig. 2, are greatest in the pressure gradient over the SV, the response of the low-level winds at
Redding to the uncertainties in the large-scale, upper-level forcing is greater than that at Bakersfield. Furthermore, there is a persistent northwesterly lower-tropospheric flow present along the northern California coast during the 5-day period (not shown). This flow tends to be blocked by the mountains to the northwest of the CV. The blocking effect, along with the dominance of the northwestern edge of the subtropical high to the southeast of the CV, results in the relatively greater pressure gradient over the northern SV than the SJV. Consequently, the low-level winds at Redding are under a relative greater influence of the atmospheric forcing than at Bakersfield. In addition to the incoming flow being moderated by the local land–surface processes as it moves up the SJV, the Tehachapi Mountains to the south of the SJV tend to block the northwesterly flow from the San Francisco Bay area, resulting in the stagnation of the flow at Bakersfield. Thus, the winds at Bakersfield tend to be affected more by land–surface processes than at Redding. It should be noted that further study is required to assess and, in particular, to quantify the relative importance of these factors.

Figure 10 presents the scatter diagrams of the winds averaged over the lowest 300 m AGL at Sacramento.
(labeled as SAC in Fig. 7). The overall sensitivity at this location is different from that at either Bakersfield or at Redding. For the winds averaged over the lowest 300 m AGL, the slope parameter of the \( u \) component is farther from 1 for the change in soil initialization than for atmospheric forcing (0.59 for soil initialization and 0.76 for atmospheric forcing), while the slope parameter of the \( v \) component is closer to 1 for the change in soil initialization (0.87) than for atmospheric forcing (0.43). Given that Sacramento is just east of the San Francisco Bay area, the \( u \) component at this location is representative of the intensity of the incoming flow through the San Francisco Bay area, while the \( v \) component is representative of the north-south splitting of the incoming flow. This sensitivity reveals that the intensity of incoming flow is more influenced by the change in the soil initialization within the CV than the north-south splitting of the incoming flow. The nonlinear response of both the \( u \) and \( v \) components of the winds averaged over the lowest 300 m AGL at Sacramento is greater to the change in atmospheric forcing than to soil initialization, as is seen at Bakersfield and Redding. This indicates that at this particular location the forcing associated with the soil initial conditions is more local than the large-scale atmospheric forcing.

The winds at Livermore (labeled LVR in Fig. 7) are representative of the incoming flow into the CV. As seen in Fig. 11, the winds averaged over the lowest 300 m AGL at Livermore are most sensitive to the atmospheric forcing since the slope parameter for the change
In atmospheric forcing is less (i.e., farther away from 1) than to soil initialization for both the $u$ and $v$ components. The slope parameters for the change in the atmospheric forcing and soil initialization for the $u$ component of the wind are less than for the $v$ component. Thus, the $u$ component of the flow is more sensitive to the atmospheric forcing and soil initialization than the $v$ component. The nonlinear response of both components of the low-level wind to the change in atmospheric forcing is greater (i.e., farther from 1) than that to soil initialization. All these imply that the intensity of the incoming flow (dominated by the $u$ component), although driven by the land–sea thermal contrast, is strongly influenced by the large-scale atmospheric forcing manifested in the pressure gradient. Estoque (1962) provided a simple but very good dynamic explanation on the impact of the large-scale pressure gradient on the intensity of locally thermal-driven flow.

**b. Patterns of differences between sensitivity to atmospheric forcing and soil initialization within the CV**

In section 3a, the scatter diagrams at four different locations within California reveal differences in sensitivity to the changes in atmospheric forcing and soil initialization. Similar scatter diagrams for 16 additional sites in and around the CV of California are done in order to obtain the patterns of the differences in sensitivity within the CV.

Figure 12 presents the difference between the slope parameters for the change in atmospheric forcing and soil initialization. For both the $u$ and $v$ component of flow.
the winds averaged over the lowest 300 m AGL (Figs. 12a,b, respectively), a distinct pattern is apparent. The negative differences of the slope parameters (emphasized with blue outlines) indicate locations where there is more sensitivity to the change in soil initialization, while the positive differences of the slope parameters indicate locations where there is more sensitivity to the change in atmospheric forcing.

For the $u$ component of the winds (Fig. 12a), the SV is more sensitive to the change in atmospheric forcing, while the SJV has more of a sensitivity to the change in soil initialization. Note that the differences in the slope parameters for sites in the SV are all positive, while several sites in the SJV are negative (Fig. 12a). Even at those sites in the northern SJV where the differences in the slope parameters are positive (including the Livermore site, which is not within the CV, but is, however, representative of the flow into the CV), the differences are small, indicating that the sensitivity to the uncertainties in the atmospheric forcing and soil initialization, as approximated by the differences in the Eta and the ECMWF analyses, are more comparable at these locations and thus there is more sensitivity to the soil initialization at these sites than those in the SV. For the $v$ component of the wind, the southern part of the SJV is more sensitive to the change in soil initialization than to atmospheric forcing (see the negative and small positive differences in the slope parameters shown in Fig. 12b), while the northern part of the SJV [north of Los Banos, California (LBA)] and the SV are more sensi-
tive to atmospheric forcing (see the positive differences in the slope parameters in the northern part of the SJV and the SV).

These distinct patterns of the sensitivity measured by the slope parameter can be interpreted as the manifestation of a difference between the linear responses of the simulated low-level winds in the SV, the northern SJV, and the southern SJV to the variation of atmospheric forcing and soil initialization. The land–sea surface thermal contrast maintains a low-level inflow of air that moves through the Carquinez Strait into the CV. The simulated intensity of this incoming flow experiences diurnal undulation and, like any locally forced flow, its temporal variation is modulated by the background, upper-level atmospheric forcing. Since the SV and the northern SJV are closer to the entrance of the incoming flow that moves through the Carquinez Strait and into the CV, the flows in these areas are more quickly influenced by this incoming flow than the southern end of the SJV. This renders the linear response of the low-level winds to the change in the atmospheric forcing stronger than to the soil initialization in the SV and the northern SJV, while the opposite is true in the southern SJV. Furthermore, since the southern part of the SJV is farther from the Carquinez Strait and more influenced by the blocking effect of the Tehachapi Mountains to the south, the incoming flow is more likely to be modified by the local land/surface processes, and therefore the low-level winds in the southern SJV have more of a linear response to the soil initialization than to the atmospheric forcing. Additionally, the upslope and downslope flows at sites along the Sierra Nevada are forced mainly by the diurnal surface radiative heating–cooling cycle. Thus, it would make sense that the low-level winds at these sites are more sensitive to the change in the soil initialization, especially in the $u$ component since these rotated wind components are perpendicular to the axis of the valley and the Sierra Nevada.

The nonlinear responses for both the $u$ and $v$ component of the low-level winds are similar to the linear responses in the SV (see the distribution of the coefficient of determination in Fig. 13). Particularly in the SV, the nonlinear responses are more sensitive to the atmospheric forcing. This is an indication that in the SV, the forcing associated with the soil initial conditions is more local than the large-scale atmospheric forcing. Furthermore, the nonlinear responses of the $u$ component of the low-level winds in the southern SJV are more sensitive to the soil initialization than to the atmospheric forcing, as is seen in the linear responses. On the other hand, the nonlinear responses of the $v$
component of the low-level winds in the southern SJV are more sensitive to the atmospheric forcing than are the linear responses. This indicates that in the SJV the $u$ component is influenced more by the local forcing associated with the soil initial conditions, while the $v$ component is more affected by the interaction of the incoming flow and the large-scale atmospheric forcing than the local forcing.

c. Spatial distribution of sensitivities to atmospheric forcing and soil initialization

Whereas section 3b focused on the sensitivity distribution in terms of whether or not a given location is more sensitive to the atmospheric forcing or to the soil initialization by examining the spatial distribution of the difference in the slope parameters, this subsection will discuss the spatial distribution of the sensitivity by examining the spatial distribution of the slope parameters themselves. In this way, the spatial distribution of the sensitivity to the uncertainties in the atmospheric forcing and the soil initialization can be discussed and explained in terms of the prominent meteorological processes occurring in this case.

Figure 14 illustrates the value of the slope parameters for the $u$ component of the wind (Fig. 14a) and the $v$ component of the wind (Fig. 14b), averaged over the lowest 300 m AGL for the ETA AIR ETA SOIL versus ETA AIR ECMWF SOIL simulation comparison (sensitivity to soil initialization). For both the $u$ and $v$ components of the wind, there is more sensitivity to soil initialization (i.e., the slope parameters are farther from 1) in the SJV than in the SV, with the largest sensitivity in the southern SJV, since the slope parameters are smallest in this area. The values of the slope parameters for the ETA AIR ETA SOIL versus ECMWF AIR ETA SOIL simulation comparison (sensitivity to atmospheric forcing) are shown in Fig. 15a ($u$ component of the wind averaged over the lowest 300 m AGL) and Fig. 15b ($v$ component of the wind averaged over the lowest 300 m AGL). For the $u$ component of the wind averaged over the lowest 300 m AGL, there is more sensitivity to the atmospheric forcing uncertainties in the SV than in the SJV, as the slope parameters in the SJV are generally closer to 1 than in the SV. However, for the $v$ component of the winds averaged over the lowest 300 m AGL, there is more sensitivity to the atmospheric forcing uncertainties in the SJV than in the SV. The areas that are most sensitive to the atmospheric forcing uncertainties are the northern SJV, followed by the southern SV.

As briefly discussed in section 3a, the distribution of the sensitivity may be explained by the meteorological conditions that control the low-level winds in each part of the CV. During the entire 5-day period of the WRF
simulations, a low-level northwesterly flow is present along the northern California coast. This low-level flow is blocked by the mountains to the northwest of the CV. Thus, the \( u \) component of the low-level winds in the SV is under the influence of the upper-level flow and its associated pressure gradient between the subtropical high and the trough off the California coast. On the other hand, the northwestern edge of the subtropical

**Fig. 15.** As in Fig. 14, but for ETA AIR ETA SOIL vs ECMWF AIR ETA SOIL simulation.
high is persistently over the SJV. This results in a relative weaker pressure gradient over the SJV and allows the $u$ component of the wind to be more influenced by local, surface-based processes. Additionally, the $u$ component of the low-level winds in the foothills of the SJV is influenced by the upslope–downslope flows associated with topographic forcing and soil thermal dynamics. Thus, one would expect the differences in the sensitivity of the $u$ components of the winds in the SV and the SJV seen in Figs. 14a and 15a. Specifically, the $u$ component of the wind is more sensitive to atmospheric forcing (the slope parameters are farther from 1) for most sites in the SV than in the SJV. The $v$ component of the wind in the SV is more affected by the down-valley–up-valley flow, while in the SJV, the $v$ component of the wind is more affected by the incoming flow. As discussed in Bao et al. (2008), the incoming flow is strongly influenced by upper-level winds, so it is no surprise that the $v$ component of the wind in the SJV (which is mostly the up-valley extension of the incoming flow) is more sensitive to the uncertainties in the upper-level atmospheric forcing associated with the upper-level winds than in the SV, as seen in Figs. 14b and 15b.

In contrast (as seen in Figs. 15a,b), the low-level winds are more sensitive to the soil initialization uncertainties in the SJV than in the SV. This is likely because most of the incoming flow veers into the SJV, and the intensity of this incoming flow is dynamically controlled by the upper-level larger-scale pressure gradient and the low-level pressure gradient force resulting from the thermal contrast between the eastern Pacific Ocean and the CV. Since the low-level winds in the SJV are dominated by the incoming flow, which is modified by the locally forced upslope–downslope flows along the foothills, they are therefore affected by the soil initialization through surface forcing. The farther south the incoming flow moves into the SJV, the more it interacts with the upslope–downslope flows along the foothills. This increased interaction along with the stagnation caused by the orographic blocking can explain why the sensitivity to the soil initialization uncertainties becomes greater in the southern SJV.

4. Discussion and conclusions

In this study, the sensitivity of the WRF model-simulated low-level winds in the CV of California to uncertainties in the large-scale atmospheric forcing and the soil initialization is investigated for a 5-day period in the summer of 2000, which is representative of the typical meteorological conditions that are favorable for poor air quality episodes in the CV. It is assumed that the uncertainties in atmospheric forcing and soil initialization can be approximated by two independent operational analyses. The sensitivity is first illustrated using scatter diagrams and measured in terms of the linear regression of one model output against another. The spatial variation of the sensitivity is investigated and linked to the dominant low-level flows within the CV.

The results from this case study strongly suggest that under typical synoptic meteorological conditions associated with poor summertime air quality in the CV, the WRF-simulated low-level winds in the SV are more sensitive to the uncertainties in the large-scale upper-level atmospheric forcing than to those in the soil initialization, while the simulated low-level winds in the southern most part of the SJV are more sensitive to the uncertainties in the soil initialization than they are to those in the large-scale upper-level atmospheric forcing. In the northern SJV–southern SV (east of the San Francisco Bay area), where the winds are relatively more directly impacted by the combination of the land–sea contrast and the large-scale upper-level pressure gradient between the westerly trough and the continental subtropical high, the simulated low-level winds are overall more sensitive to the uncertainties in the large-scale upper-level atmospheric forcing than to those in the soil initialization. The sensitivity results in general reveal the importance of not only the impact of the uncertainties in the surface thermal contrast between the CV and the Pacific Ocean on the incoming flow through the San Francisco Bay area, but also the interaction between this incoming flow, the large-scale upper-level pressure gradient and local-scale slope flows along the foothills of the CV.

It is a widely accepted notion that an accurate specification of the soil initialization is important to the simulation of locally forced low-level winds. Our study not only reinforces this notion but also strongly suggests that it is the interaction of the valley-scale wind associated with the incoming flow and the locally forced winds along the foothills that determines winds in the CV and therefore the overall transport and dispersion of pollutants across the valley. Thus, future effort to improve the accuracy of the WRF-simulated low-level winds in the CV should focus on the identification of not only the error sources of the simulated locally forced winds but also the error sources of the upper-level winds and their large-scale forcing (such as the upper-level high located above the CV and the trough to the northwest of the CV).

It is cautioned that sensitivity results from this study only pertain to the particular case in question. Further studies are required to investigate how general the re-
results are and whether the results vary seasonally and annually. Other nonderivative approaches for sensitivity analysis should also be explored to ensure the robustness of the physical meaning of the results.

REFERENCES


