An Evaluation of a Diagnostic Wind Model (CALMET)

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ABSTRACT

A U.S. Environmental Protection Agency (EPA)-approved diagnostic wind model [California Meteorological Model (CALMET)] was evaluated during a typical lake-breeze event under fair weather conditions in the Chicago region. The authors focused on the performance of CALMET in terms of simulating winds that were highly variable in space and time. The reference winds were generated by the fifth-generation Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model (MM5) assimilating system, with which CALMET results were compared. Statistical evaluations were conducted to quantify overall model differences in wind speed and direction over the domain. Below 850 m above the surface, relative differences in (layer averaged) wind speed were about 25%–40% during the simulation period; wind direction differences generally ranged from 6° to 20°. Above 850 m, the differences became larger because of the limited number of upper-air stations near the studied domain. Analyses implied that model differences were dependent on time because of time-dependent spatial variability in winds. Trajectory analyses were made to examine the likely spatial dependence of CALMET deviations from the reference winds within the domain. These analyses suggest that the quality of CALMET winds in local areas depended on their proximity to the lake-breeze front position. Large deviations usually occurred near the front area, where observations cannot resolve the spatial variability of wind, or in the fringe of the domain, where observations are lacking. Results simulated using different datasets and model options were also compared. Differences between CALMET and the reference winds tended to be reduced with data sampled from more stations or from more uniformly distributed stations. Suggestions are offered for further improving or interpreting CALMET results under complex wind conditions in the Chicago region, which may also apply to other regions.

1. Introduction

The release of chemical, biological, radiological, or other hazardous materials accidentally or intentionally usually generates emergency situations. Modeling atmospheric transport and diffusion of these materials is a necessity for emergency response. The accurate calculation of dispersion is in turn dependent on the input of an accurate atmospheric wind field. With the current state of computer technology, numerical atmospheric models such as the well-known fifth-generation nonhydrostatic Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model (MM5; Dudhia 1993; Grell et al. 1994), Weather Research Forecast Model (WRF; Skamarock et al. 2005), and Regional Atmospheric Modeling system (RAMS; Pielke et al. 1992; Cotton et al. 2003) need less computation time than years ago and can reasonably forecast as well as diagnose airflow under complex conditions. While the forecast capability of these models is a distinct advantage, and they are beginning to be used for the purpose of operational decision making, their output is not yet routinely accessible for emergency response by all jurisdictions. In this regard, diagnostic wind models based on mass conservation still play an indispensable role because of their fast computation and relative ease of use by local agencies. One such diagnostic model is the California Meteorological Model (CALMET) that is usually used to provide meteorological fields to dispersion models. For instance, the California Puff Model (CALPUFF) system, which is approved by the U.S. Environmental Protection Agency (EPA) for regulatory applications (http://www.epa.gov/scram001/guidance/guide/appw_05.pdf), uses wind fields provided by CALMET to simulate the transport and dispersion of pollutants (Scire et al. 1998).
Calmet has been evaluated with observations at a limited number of surface stations in a case study by Cox et al. (2005). The ability of Calmet to simulate wind fields under complex conditions, however, has not been extensively evaluated because three-dimensional data with a high spatial resolution that can characterize spatial and temporal changes in wind fields are difficult to obtain. To resolve this difficulty, we assumed in this study that the assimilated wind fields generated by a physics-based state-of-the-science model can represent real wind fields to a good approximation. We then evaluated the capability of Calmet to replicate these wind fields when Calmet was supplied with model output “sampled” at locations of existing meteorological stations in the Chicago area. In this case study, MM5–four-dimensional data assimilation (FDDA) was used to simulate wind fields. The MM5–FDDA system optimally combines atmospheric dynamics and observational data. It has been shown in earlier studies to be able to reasonably reproduce real wind fields under complex conditions (e.g., Grell et al. 1994; Stauffer and Seaman 1994; Seaman et al. 1995; Shafran et al. 2000; Deng et al. 2004).

Our evaluation involved three basic steps. First, three-dimensional wind fields were simulated by MM5–FDDA. The computed wind fields are called the “reference wind fields” hereinafter. Second, wind “data” from actual locations of surface and upper-air stations in the Chicago area were sampled from the reference wind fields. The resulting time series from multiple locations became the input to Calmet, which we have run with different model options and sampled data. Finally, statistical evaluations were made by comparing grid values from the Calmet model with those from the reference data. We would like to partially address the following practical questions: 1) What are the differences between Calmet results and the reference data if only regular observation data from the National Weather Service (NWS) are used in an area with sometimes complicated wind patterns resulting from a lake breeze? 2) How may the differences vary temporally and spatially? 3) To what degree does adding more observation stations from other available observation networks improve wind field results? 4) What are the impacts of Calmet parameter settings on wind simulations in the studied region?

2. Model descriptions and methods

a. MM5–FDDA configuration

The mesoscale model (MM5–FDDA) uses a terrain-following sigma (nondimensionalized pressure) coordinate system and contains prognostic equations for three wind components, temperature, and the water vapor mixing ratio. A split semi-implicit temporal integration scheme is used. For this study, we used three nested domains. The outermost domain had 61 × 61 points and 36-km resolution. The intermediate domain had 85 × 70 points and 12-km resolution; the innermost domain had 85 × 70 points and 4-km resolution. All domains had 39 vertical layers with approximately 20 layers below 850 hPa. The model domain was centered at Chicago, Illinois (approximately 41.92°N, 87.84°W). The vertical grid sizes increased gradually with height with the lowest level being at 10 m above the ground. The model top was located at 100 hPa. All three domains used an explicit microphysical scheme with a simple ice phase (Dudhia 1989) to represent resolved possible saturated processes. The Grell scheme (Grell et al. 1994) was used to represent deep convection on the domains with 36- and 12-km resolutions. The innermost domain did not use parameterized convection but used the explicit microphysics. A cloud–radiation scheme (Dudhia 1989) accounts for longwave and shortwave interactions with explicit cloud and clear air as well as atmospheric temperature tendencies. The atmospheric boundary layer scheme implemented in the National Centers for Environmental Prediction (NCEP) Medium-Range Forecast (MRF) Model was used in this study (Hong and Pan 1996) to represent turbulent fluxes of heat, moisture, and momentum. The ground temperature was simulated by a five-layer soil model, where temperature was predicted in 1-, 2-, 4-, 8-, and 16-cm layers with fixed substrate below using the vertical diffusion equation (Dudhia 1996). Surface fluxes were calculated using Monin–Obukhov similarity theory (Stull 1988). Initial and lateral boundary conditions were specified from objective analyses on the outermost domain. The Global Final (FNL) analyses on 1.0° × 1.0° grids covering the entire globe every 6 h generated by NCEP and standard surface and radiosonde observations from the NWS were used to prepare the three-dimensional initial conditions and lateral conditions for meteorological fields. Two-dimensional surface meteorological fields were generated at 3-h intervals.

The synoptic-scale analyses were assimilated via analysis nudging on the 36- and 12-km grids. The nudging coefficient $G$ determines the e-folding rate of assimilation. On the 36-km grid domain, $G$ was set to $2.5 \times 10^{-4} \text{ s}^{-1}$ for wind and temperature and $1.0 \times 10^{-5} \text{ s}^{-1}$ for moisture. On the 12-km domain, $G$ was reduced for wind and temperature to $1.0 \times 10^{-5} \text{ s}^{-1}$ because the large-scale results may not be able to resolve features...
on the finer grid scale. In addition, 3-h surface wind analyses were assimilated within the boundary layer (Stauffer et al. 1991). On the 4-km domain, surface wind data from NWS stations were assimilated via observation nudging. The nudging coefficient used was $4.0 \times 10^{-4} \text{s}^{-1}$ for wind. Surface temperatures were not assimilated in consideration of likely unreasonable impacts on the boundary layer structure (Stauffer and Seaman 1994). It should be noted that it is not our goal to test the MM5 system in this study. Instead, we used typical model options that have been successfully used by investigators to generate reasonable wind fields and to test how well the CALMET model can generate reasonably similar fields.

b. CALMET

CALMET is a diagnostic meteorological model that generates mass-consistent wind fields. In general, three steps are included in the model. The first step is to interpolate or extrapolate observed wind data to grid points in the domain under study. The second step is to use parameterizations to account for the kinematical effects of terrain, slope flows, and blocking effects. The third step is to adjust wind fields to meet the mass consistency requirement. Details about the model are given by Scire et al. (1998). Our simulation domain was $100 \text{ km} \times 100 \text{ km}$ (Fig. 1), covering part of the Chicago region. The horizontal grid size was 4 km. Ten grid cells were used in the vertical direction with the grid size increasing from near the surface to higher levels. The cell face heights were 0, 20, 30, 50, 90, 180, 300, 600, 1100, 2000, and 4000 m. In the following evaluation, five model settings (summarized in Table 1 and discussed below) were designed to examine the impacts of model parameters on wind field simulations.

Model option defaults given by CALMET (Scire et al. 1998) were used in S0 (“S” refers to “setting” and “0” to the first, or baseline, model setting in Table 1). In S1, layer-dependent weights, represented by the parameter BIAS, were used to combine data from surface and upper-air stations to form the interpolated winds. The spatially variable wind field was computed as an inverse distance-squared weighting of the surface and upper-air observations, modified by BIAS values that ranged from $-1$ (i.e., weighting of the upper-air station wind is reduced to zero) to 1 (i.e., weighting of the surface station is reduced to zero). A value of zero for the BIAS resulted in no change of weight from the normal inverse distance-squared weighting of the surface and upper-air observations.

Table 1. Model settings: $R_1$ is the distance from an observational station in the surface layer at which the observation and first guess field are equally weighted; $R_2$ is applied in the upper layers in the same manner as $R_1$; $R_{\text{max}1}$ and $R_{\text{max}2}$ are the maximum radii of influence of stations over land in the surface layer and aloft, respectively. More details can be found in the CALMET manual (Scire et al. 1998). Default BIAS values are equal to zero for all levels above the surface. On the surface level, all BIAS values are equal to $-1$, meaning that upper-air observations have no impacts in surface wind calculations.

<table>
<thead>
<tr>
<th>Name</th>
<th>Model options</th>
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<tbody>
<tr>
<td>S0</td>
<td>Model defaults with $R_{\text{max}1} = 50$ km, $R_{\text{max}2} = 500$ km, $R_1 = R_2 = 1$ km</td>
</tr>
<tr>
<td>S1</td>
<td>Same as S0, but for BIAS = $-1$, 0.2, 0.3, 0.4, 0.4, 0.5, 0.8, 1.0, 1.0</td>
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</table>
The horizontal winds were then adjusted by a divergence minimization scheme (Scire et al. 1998). In S4, the lake-breeze option was used for interpolating the surface wind field in the domain, where the distances for the inverse distance–squared interpolation were defined as the difference between the distances of the grid point to the shoreline and the station to the coastline if the station and grid point are on the same side of the shoreline and the sum if they are on opposite sides (Scire et al. 1998).

Data availability and density, particularly from surface stations, are key factors affecting wind field results in addition to model option settings. Experiments were made to examine the effects of different datasets on results. Datasets were constructed by using various combinations of surface network sensor locations to sample the reference wind field. Because there was no regular NWS upper-air station available within the CALMET domain under study, we used data from the five nearest upper-air stations (Fig. 2). Nine conventional NWS surface stations were located in the CALMET domain in addition to 35 surface stations available through the MesoWest meteorological observation network (http://www.met.utah.edu/mesowest; Horel et al. 2002).

For the following evaluation, we ran CALMET using different combinations of model settings (Table 1) and datasets (Table 2). D1 included data sampled from the locations of regular NWS stations ("D" refers to "dataset", and "1" to the first dataset in Table 2; we used analogous nomenclature for the other datasets). Model setting S0 and dataset D1 were used in the control run. In D2, data sampled from the locations of both NWS and MesoWest stations were used because we intended to determine the degree to which CALMET fields can be improved with a significantly but realistically increased number of surface stations. For D3, we further assumed that observations from three locations at the corners of the domain (asterisks in Fig. 1) were available in addition to data from regular NWS station locations because we found that there were no available stations in the three corners. This experimental designation was based on our hypothesis that the distribution of stations may be as important as the number of stations in terms of improving the diagnosed results. In D4 and D5, we assumed that wind data from a sodar profile were available at the center of the domain (Fig. 1) in addition to the data in D2 and D3, respectively. Experiments with D4 and D5 were designed to see if adding an additional sodar profile can improve the wind fields above the surface.

To generally characterize the spatial distribution of the locations of the surface observational stations for each dataset, we introduced two quantities in addition to the number of stations: the median distance (MD) between adjacent stations and the index of spatial distribution (ISD) of stations. The MD provides a measure of how close the stations are to each other overall for a given domain. A larger MD value indicates that stations are more widely separated. In general, observations from more closely distributed stations can resolve a finer scale of spatial variability in winds. ISD indicates how uniformly the stations are distributed in the given domain. ISD ranges from a small fraction greater than zero to a value of one. A larger ISD value indicates that stations are more uniformly distributed over the given domain. Using observations from less uniformly distributed stations in CALMET may lead to significant differences between CALMET winds and the reference data in local areas where no stations are presented. The appendix describes the calculation of MD and ISD more specifically. In this study, NWS_MESO (D2) station locations are the most closely but least uniformly distributed in our domain under study, with NWS_PLUS (D3) being the least closely but most uniformly distributed among three datasets (Table 2). The following analysis shows how the spatial distribution of stations affects CALMET results.
3. Experimental results

a. Overview of the selected case

The case chosen for the study is an episode over 9–10 July 2005. The Chicago region was controlled by a high pressure center with a light synoptic-scale airflow at 500 hPa that was generally from the northwest. Under these fair-weather conditions, a well-defined lake breeze occurred. MM5–FDDA results indicated that the surface wind direction in the shoreline area started to gradually change in the morning [roughly 0700 local standard time (LST)] from southeast to east and then to northeast. A lake-breeze front formed approximately at 0800 LST and moved inland. With the decrease of solar energy in the late afternoon, the strength of the breeze was reduced, but the lake breeze continued to move inland until early evening. The lake breeze swept over the whole CALMET domain after 2000 LST. The depth of the lake breeze reached about 850 m in the late afternoon. At midnight, the surface wind component from east was significantly reduced and the surface wind blew from south or southeast in most of the domain. In the early morning of the next day, the surface wind turned to be generally from the southwest. The nighttime winds were in general weaker than daytime lake breeze.

The MM5–FDDA simulation was run for 60 h to produce the reference wind fields starting from 0000 UTC 9 July 2005 (LST). Figure 3 presents the surface wind vectors and wind vectors in vertical cross section, indicating the evolution of the lake breeze. During the simulation period, the mean absolute surface wind direction difference between the MM5 results and NWS observations is about 20°, and the mean absolute wind speed difference is about 1.2 m s⁻¹. To emphasize wind field variability in the analysis, only results from 0400 LST 9 July to 0900 LST 10 July 2005 were selected to run CALMET and make comparisons (to properly approximate the mixed layer depth from assumed diurnal surface heating, CALMET requires a starting time that is earlier than 0500 LST). Figure 4 presents wind vectors simulated from CALMET, suggesting that CALMET can reasonably diagnose the evolution of winds as compared with the reference wind in Fig. 3.

b. Evaluation methods

The performance of CALMET was assessed with two methods. One was an overall statistical evaluation, which included an analysis of time-varying differences between CALMET results and the reference data. The other was a comparison of the trajectories of parcels (pollutants) driven by CALMET wind fields with those driven by the reference wind fields. This approach provided a measure of the practical effect that differences of CALMET winds from the reference data had on plume calculations. We employed the following statistical measures to assess the overall model performance: the root-mean-square (RMS) of vector wind difference (VWD), the relative mean absolute difference (MAD) between CALMET wind speed and the reference wind speed (Stauffer et al. 1991), the agreement index (AI) of wind speed (Willmott 1981, 1982; Willmott et al. 1985), the fractional number of grids where the ratio of wind speeds from CALMET to the reference data is between 0.5 and 2 (FAC2; Hanna et al. 1993), and the absolute vector-mean wind direction difference (VMWDD). RMS VWD combines differences in wind direction and speed, which is particularly useful in comparing model performance from different experiments. To calculate the statistics, the reference wind fields have been interpolated to the CALMET grids. The formulas for calculating statistics and interpretations are given in the appendix.

c. Results and analyses

1) Statistical evaluation

(i) Surface wind fields

For a given dataset, CALMET yielded the same surface wind fields when model settings S0, S1, or S2 were used, because winds aloft were not allowed to
FIG. 3. MM5–FDDA horizontal wind vectors at 10 m above the ground at (a) 0800, (b) 1200, and (c) 1600 LST 9 Jul and (d) 0500 LST 10 Jul 2005. The thin line represents approximate position of shoreline. Vertical cross section of wind vectors below 1500 m above the ground at location $y = 4650$ km at (e) 0800, (f) 1200, (g) 1600, and (h) 0500 LST. The triangle represents the location of boundary of water and land on the surface. Results have been interpolated to the vertical levels of CALMET.
Fig. 4. As in Fig. 3 except that wind results are simulated from CALMET with NWS and MesoWest datasets (D2S1).
influence the surface wind field with these settings. Surface wind results with model setting S3 or S4 may be different from those with model setting S0. Given model settings other than invoking the O'Brien procedure (S3), CALMET surface wind fields with D4 and D5 were the same as those with D2 and D3, respectively, because the sodar profile data were treated as observations from an upper-air station in our calculation. We calculated the differences in surface winds from CALMET and the reference data over the entire domain for each hour. Table 3 presents and compares the first quartile (Q1), median (MED), and third quartile (Q3) of the hourly model differences during the simulation period for different experiments.

We used the median values from Table 3 to characterize the success of the CALMET model in estimating surface wind fields during the whole simulation period. The median values of RMS VWD, calculated from all surface grid nodes, ranged from 0.7 to 1.2 m s\(^{-1}\) over the 30-h period of the comparison. Median values of the relative MAD in wind speed were about 20%–30%, the vector mean wind direction differences ranged from 5° to 20°, and the indexes of agreement were between 60% and 75%. Wind speeds at more than 90% of grids were within a factor of 2 of the reference data. Taken together, these statistics capture the overall performance of CALMET for simulating complex surface wind fields.

The performance of CALMET depended on the data and model settings selected. The control run (D1S0) yielded the largest differences in both wind speed and wind direction from the reference wind data; this is probably because the number of NWS surface stations is too small to characterize well the spatial variability in wind fields for this lake-breeze case. When data from the locations of MesoWest surface stations were added, the differences between CALMET winds and the reference winds were generally reduced. This was particularly true for wind direction. NWS_MESO data were sampled from more surface locations than NWS data, and therefore finer-scale spatial variability in winds can be resolved. The wind differences can be reduced significantly at least in some local areas (e.g., near MesoWest stations). Interestingly, experiments with data only from 12 stations (NWS_PLUS) yielded results (Table 3) roughly equivalent to those derived from the 44 NWS_MESO stations. This suggests that simply adding more stations may not always significantly improve overall results, and surface wind field diagnosis at some grid points within the domain may not benefit significantly from the added stations from MesoWest (since the wind field was not homogeneous in space).

We note that NWS_MESO stations are less uniformly distributed than NWS_PLUS stations despite there being more sampling locations in the NWS_MESO dataset (Table 2). This indicates that the distribution, in addition to the number, of surface stations is an important factor affecting the overall performance of CALMET for this lake-breeze case.

With regard to the operational impacts of model options, running CALMET with the O'Brien procedure (model setting S3) took about 50 times longer than any other model settings but did not significantly improve results. As a result, this model option is not recommended for use in the region under study. Using the see-breeze model setting (S4) in CALMET did not ne-
nessarily yield better results either, and the results were even worse in some cases. These comparisons suggest that the quality of CALMET surface wind fields in this region is more sensitive to the characteristics of the observation network (number and distribution of stations) than to model setting selection.

Because the spatial distribution of the surface wind significantly varied with time in this lake-breeze case, it was expected that the differences between CALMET winds and the reference winds were dependent on time, too. Figures 5a–c show RMS VWD, relative MAD, and wind direction difference as a function of time for the 30-h comparison period. In addition, Fig. 5d shows RMS of vector wind differences between the reference winds at the grids and their mean values over the domain relative to vector-mean reference wind speed, which is used to measure spatial variability of the reference wind. Abbreviated dataset names are shown for convenience of comparisons. Time 0000 is the beginning of the next day.

As an example, we show the time series of wind vectors (Fig. 6) at a grid point (whose position is shown as the triangle in Fig. 1) from different experiments compared with the reference data. The values of RMS of vector wind differences between CALMET results and the reference winds at the point during the 30-h period were also shown in the figure. Using data from current NWS stations can produce reasonable wind results compared to the reference wind field. Adding more
data from MesoWest further improved the results (D2S0), which resulted in the smallest RMS VWD (and hence the best wind results) among the cases in the figure. In addition, we will show in section 3c(2) that the differences between CALMET winds and the reference winds vary greatly within the domain because of the high spatial variability of winds. Therefore, this example does not represent results in the entire domain.

(ii) Wind fields above the surface

In CALMET, surface characteristics can affect the wind field above the surface to some extent. The weights of surface wind observations to interpolated winds at higher levels are controlled mostly by the parameter BIAS in CALMET (section 2b). Determining the values of BIAS is somewhat subjective. Different BIAS values may generate significant differences in the wind fields above the surface. We calculated RMS VWD, relative MAD, VMWDD, AI, and FAC2 for CALMET wind fields versus the reference data over all vertical levels from 25 to 850 m above the surface at each hour in the same manner as the calculation for surface winds in the previous section. Table 4 presents the first, second, and third quartiles of the model differences during the 30-h modeling period.

For all cases, median values of relative differences in wind speed were between 25% and 40%. The agreement indexes of grid wind speeds were approximately 50%–65%. CALMET wind speed values at approximately 80%–95% of the grids were within a factor of 2 of the reference data. Wind direction differences were about 6° to 15°. The median values of RMS VWD, combining differences in direction and speed, ranged from 1.2 to 1.8 m s⁻¹. In terms of overall statistics, CALMET had worse performance for reproducing wind fields above the surface than at the surface.

Model differences in wind fields above the surface varied with time, as shown in Figs. 7a–c. First, wind direction differences had significant diurnal patterns that were similar to those for surface winds. Before the lake breeze covered the whole domain or at the very late stage of the lake breeze (when the lake-associated breeze is weak), wind direction differences were larger than at other times of the simulation period. When the spatial variability of the reference wind field was small (e.g., from 1900 to 0300 LST as suggested in Fig. 7d), adding data from the sodar profile did improve CALMET results above the surface (diamonds and asterisks in Figs. 7a–c). When the spatial variability was large (e.g., the lake-breeze front is moving in the central area of the domain; Fig. 7d), using data from more surface stations can improve CALMET results (squares and triangles in Fig. 7) while adding data from a single sodar profile may not necessarily do so. Second, impacts of BIAS values on the diagnosed wind results depended on time of the day. In terms of RMS VWD, using BIAS values in S1 yielded the best result roughly from the early morning to late afternoon (1700 LST) when the lake breeze was developing. Using the default BIAS values in S0 yielded the best result during nighttime. The temporal dependence of the differences between CALMET winds and the reference winds was most likely owing to the time-dependent wind field vertical structure. For a lake-breeze situation, the wind speed changes significantly with height and wind direction in the high levels can be opposite to that on the surface. As a result, less weighting of the surface wind at upper levels, as is the case for default BIAS values, yields smaller differences. Significant wind direction changes did not occur in our reference data at night, which probably was a reason why using default BIAS can get better results during nighttime. It should be noted that the effects of using different BIAS values on wind field diagnoses is site-dependent because dominant local flow features will vary. Nevertheless, the above comparisons suggest that simply using default BIAS values given by CALMET is inappropriate. In practice, some experimenting with BIAS values based on wind field features for a specific site is helpful for improving the simulation of wind fields above the surface.

Figure 8 shows the time series of wind vectors at 240 m above the surface from the same grid point as in Fig.
We have shown in the first part of this section that using different datasets affects surface wind fields calculated by CALMET. Different datasets of surface sampling locations also affect wind fields above the surface through the parameter BIAS. To illustrate this, we compared model results with BIAS values in model setting S1 using different datasets (D1–D5). Similar to the case for the surface wind comparisons, using data only from NWS station locations yielded the largest RMS VWD below 100 m; this was because lower-altitude wind fields are strongly correlated with those at the surface (10 m). The overall performance of CALMET using data from NWS_PLUS (D3S1) was equivalent to that using data from NWS_MESO (D2S1), which was less uniformly distributed than NWS_PLUS; this was also similar to the comparison in the previous section.

Adding one sodar profile can improve the overall predictions of wind field below the lake-breeze depth of 850 m in terms of RMS VWD. It is expected that adding more vertical profiles, if possible, can further improve the results. Because there were no upper-air stations available in the CALMET domain, differences between CALMET winds and the reference winds were significantly larger above 850 m than below. The wind direction difference can be 100° and relative wind speed difference can be as large as 200%. Lack of observations above 850 m within the domain is a major reason for such large differences in wind direction and wind speed (Fig. 9). Adding sodar data cannot improve the wind diagnosis above 850 m, either, because sodar profiles usually provide wind data only below approximately 500 m.

### Table 4. Statistics distribution of model differences for layers from 25 to 850 m during the modeling period.

<table>
<thead>
<tr>
<th>Expts</th>
<th>RMS VWD (m s^{-1}) MED (Q1, Q3)</th>
<th>Relative MAD MED (Q1, Q3)</th>
<th>VMWDD (deg) MED (Q1, Q3)</th>
<th>AI MED FAC2 MED (Q1, Q3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D5S0</td>
<td>1.704 (1.150, 2.612) 0.366 (0.231, 0.643) 14.3 (5.92, 34.3) 0.563 (0.370, 0.683) 0.838 (0.632, 0.994)</td>
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</tr>
<tr>
<td>S1</td>
<td>1.494 (1.147, 2.042) 0.387 (0.284, 0.459) 11.1 (4.26, 25.9) 0.504 (0.426, 0.621) 0.849 (0.704, 0.952)</td>
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<tr>
<td>S2</td>
<td>1.532 (1.099, 2.330) 0.371 (0.247, 0.478) 15.3 (6.04, 36.0) 0.504 (0.399, 0.643) 0.831 (0.683, 0.968)</td>
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<tr>
<td>S3</td>
<td>1.496 (1.143, 2.060) 0.384 (0.288, 0.456) 11.0 (4.18, 26.0) 0.498 (0.419, 0.612) 0.852 (0.702, 0.946)</td>
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<tr>
<td>D4S0</td>
<td>1.491 (0.983, 2.410) 0.280 (0.187, 0.710) 9.92 (2.62, 20.3) 0.576 (0.422, 0.785) 0.904 (0.747, 1.000)</td>
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<tr>
<td>S1</td>
<td>1.293 (1.025, 1.921) 0.308 (0.213, 0.407) 9.43 (5.00, 19.5) 0.542 (0.444, 0.753) 0.910 (0.835, 0.997)</td>
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<tr>
<td>S2</td>
<td>1.371 (0.942, 2.134) 0.279 (0.191, 0.443) 13.3 (3.70, 30.7) 0.544 (0.422, 0.785) 0.904 (0.747, 1.000)</td>
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<tr>
<td>S3</td>
<td>1.312 (1.029, 1.922) 0.317 (0.221, 0.410) 9.40 (4.98, 19.6) 0.535 (0.449, 0.744) 0.905 (0.832, 0.994)</td>
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<tr>
<td>D3S0</td>
<td>1.376 (0.860, 2.358) 0.321 (0.199, 0.635) 9.31 (2.98, 21.5) 0.649 (0.415, 0.784) 0.859 (0.694, 1.000)</td>
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<tr>
<td>S1</td>
<td>1.311 (1.015, 2.018) 0.370 (0.260, 0.436) 11.5 (5.20, 23.7) 0.551 (0.476, 0.705) 0.880 (0.742, 0.998)</td>
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<tr>
<td>S2</td>
<td>1.361 (0.883, 2.293) 0.352 (0.227, 0.471) 14.0 (4.47, 33.9) 0.563 (0.422, 0.739) 0.858 (0.725, 1.000)</td>
<td></td>
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<tr>
<td>S3</td>
<td>1.310 (1.025, 2.013) 0.372 (0.264, 0.440) 11.6 (5.29, 23.5) 0.545 (0.481, 0.690) 0.877 (0.746, 0.997)</td>
<td></td>
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</tr>
<tr>
<td>D4S0</td>
<td>1.481 (0.965, 2.360) 0.278 (0.184, 0.686) 9.93 (2.63, 20.32) 0.584 (0.367, 0.787) 0.910 (0.645, 1.000)</td>
<td></td>
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</tr>
<tr>
<td>S1</td>
<td>1.254 (0.849, 1.639) 0.250 (0.184, 0.357) 7.0 (2.44, 18.79) 0.587 (0.441, 0.761) 0.957 (0.826, 1.000)</td>
<td></td>
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</tr>
<tr>
<td>S2</td>
<td>1.246 (0.868, 1.667) 0.251 (0.191, 0.361) 6.7 (2.54, 20.85) 0.565 (0.484, 0.795) 0.942 (0.813, 1.000)</td>
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<tr>
<td>S3</td>
<td>1.256 (0.839, 1.635) 0.250 (0.189, 0.349) 7.0 (2.45, 18.65) 0.577 (0.439, 0.758) 0.955 (0.835, 1.000)</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>D5S0</td>
<td>1.355 (0.842, 2.170) 0.302 (0.194, 0.552) 9.00 (2.70, 22.4) 0.660 (0.444, 0.781) 0.877 (0.741, 1.000)</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>S1</td>
<td>1.241 (0.822, 1.608) 0.264 (0.202, 0.386) 6.19 (2.14, 19.12) 0.624 (0.516, 0.740) 0.932 (0.787, 1.000)</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>S2</td>
<td>1.242 (0.809, 1.642) 0.279 (0.209, 0.394) 6.11 (2.32, 22.3) 0.620 (0.460, 0.746) 0.921 (0.778, 1.000)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S3</td>
<td>1.236 (0.821, 1.633) 0.263 (0.202, 0.389) 6.24 (2.17, 19.1) 0.614 (0.507, 0.735) 0.941 (0.784, 1.000)</td>
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</tbody>
</table>
The vertical component of wind is also important to simulating the transport of pollutants under complex meteorological conditions. Our statistics show that the CALMET model can simulate wind components in the horizontal direction better than in the vertical direction. This is consistent with previous evaluations (Chang et al. 2003; Cox et al. 2005). Overall, the magnitude of the vertical velocity from CALMET was smaller at the lower levels and higher at higher levels than that from the reference MM5 simulation, respectively. This is because data sampled from the limited number of surface and, particularly, upper-air stations cannot resolve fine structures of winds. The lack of thermodynamic information in diagnostic modeling is also an important limitation. As a result, vertical velocity is not typically used in applied models. Instead, the center of mass of advected puff is adjusted vertically by vertical diffusion.

2) TRAJECTORY COMPARISONS

Accidental releases of pollutants usually occur within a limited area at a specific time and then influence adjacent and remote areas because of atmospheric transport and dispersion processes. It is important to understand how confident we are in predicting wind fields near the location of such a release, because wind direction and speed are among the most important variables that determine where the pollutants will be carried. In this regard, overall statistical evaluation may be insufficient to assess whether a model could be useful to help decision makers respond to individual events.
Therefore, we further examined the performance of CALMET by comparing the trajectories of individual pollutant parcels driven by the wind fields from CALMET and from the reference data. Trajectory analyses integrate the effects of temporally and spatially varying wind fields. They also provide a good indication of how well dispersion calculated using CALMET wind fields is likely to match actual dispersion. In the comparisons that follow, the trajectory driven by the reference wind field is called the reference trajectory.

We examined surface horizontal wind fields simulated from CALMET by comparing two-dimensional horizontal trajectories driven by CALMET winds with the corresponding reference trajectories. The time step in the calculation is 10 s. Parcels of pollutant were assumed to be released at 10 m above the surface from five locations in the domain under study (Fig. 10). The trajectories of those parcels were calculated using the horizontal west–east and south–north wind components created by CALMET. In other words, the pollutant cloud centerline was assumed to follow a constant height above the terrain. This algorithm is the same as one of the options available in the CALPUFF modeling system (Scire et al. 1998; Cox et al. 2005).

As an example, Fig. 10 presents the 4-h trajectories of single parcels instantaneously released at 1400 LST from five locations. Each line in the figure represents the mean trajectory of each of the released parcels. Turbulence is not considered. We selected the five release locations and 1400 LST as the release time for the following reason. Statistical analyses in the previous section suggest that the quality of wind fields simulated by CALMET depends on time due to variability related to the lake-breeze circulation and, in particular, the lake-breeze front. The front, moving to the southwest, reached the middle of the domain at 1400 LST for this case (see the gray long-dashed line in Fig. 10). The 4-h trajectories of the parcels released from locations (A, B, and both C and D) at 1400 LST are expected to represent wind field characteristics for local areas before, during, and after the passage of the lake-breeze front, respectively. Location E represents a site over the lake.

The lake-breeze front did not reach location A during the 4-h period of interest, but the westerly component of the wind diminished with time in response to the overall lake-breeze circulation. Based on the reference wind data, a parcel would have been first carried to the north and then to the east (thick gray line). The direction of the parcel trajectory driven by the wind field from CALMET using NWS_MESO data (D2S0) was the closest to that of the reference trajectory among the results from the four experiments. The lengths of the trajectories in all experiments were shorter than the reference trajectory length at this location, indicating that the wind speed was underestimated by CALMET in this area. Using the lake-breeze option (D2S4) in CALMET did not seem to improve the results in this case, where the trajectory deviated about 45° to the east relative to the reference. CALMET wind fields using data sampled only from NWS station locations (D1S0) and from NWS_PLUS locations (D3S0) drove parcel trajectories 45° to the west compared to the reference. This suggests that some local variations of the wind field near A cannot be resolved by observations from the sparsely distributed NWS stations.

The lake-breeze front passed location B during the 4-h period. The reference trajectory implied that the parcel was carried northeast before the arrival of the front and then to the northwest after the front passed. Significant variation in the trajectory direction was due to the highly variable winds during the front’s passage. As a result of the lack of observing sites in the area, CALMET was unable to reproduce the westerly wind component ahead of the front when we used data sampled from NWS station locations (D1S0) or from the NWS_MESO locations (D2S0). This produced significant differences in the parcel trajectory when compared with the reference trajectory. When we added a sampling station to the northwest corner (D3S0), the
Trajectory calculation was improved, at least in the initial one or two hours. Using the lake-breeze option (D2S4) also improved results in this case.

The lake-breeze front had passed locations C and D when pollutant parcels were released. Location E (over the water) is always behind the front. As a result, the temporal changes in wind speed or wind direction were smaller at these locations than at B. At locations C and D, the parcel trajectory directions were generally consistent with those derived from the reference data since the parcels were released into surface wind fields that were relatively uniform, steady, and well sampled. At D, all cases yielded reasonable results. At C, trajectories projected from CALMET wind fields using all datasets were about 20°–30° north of the reference trajectory. At this location, CALMET with the lake-breeze option (D2S4) yielded the best results and significantly improved the results that compared with

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**FIG. 9.** Median values of the differences between CALMET winds and the reference winds during the simulation period at each vertical level. Lines represent results obtained using different model options (Table 1) and datasets (Table 2). The simulation time starts from 0400 LST. Results using D1S0 are from the control run. In the legend, abbreviated dataset names are shown for convenience of comparison. Effects of model settings are compared among D1S0, D1S1, and D1S2 for a given dataset (D1). Effects of datasets are compared among D1S1, D2S1, D3S1, D4S1, and D5S1 for a given model setting (S1).
those in which the lake-breeze option was not used (D1S0, D2S0, D3S0). In contrast to locations C and D, CALMET wind fields at location E using data sampled from the NWS locations and from the NWS_MESO locations still yielded differences (60° deviation to the south) in the trajectory direction compared with the reference trajectory that were as large as those at B, though the wind field was more steady than at B, which was strongly affected by the front. This is most likely because of the lack of observing sites near E and suggests that observations from the current networks cannot reliably be used to calculate wind field features in this area. The trajectory difference was reduced when one observational station was added in the northeast corner (D3S0). This is similar to case B and illustrates that the spatial distribution of stations is important. Using the lake-breeze option (D2S4) did not improve the results at E. These results suggest that measurements from the current networks can reasonably represent the surface wind fields once the front has passes, as we found at C and D, though some small-scale features still cannot be resolved by CALMET results—either because the influence radius of stations is too large or because the observation stations are too sparse.

4. Summary

We have examined an application of CALMET to the strongly varying wind field associated with a lake-breeze event in the Chicago region. In general, CALMET can reasonably simulate wind fields using the currently available observation networks. We compared winds from CALMET with those from the reference data, and model differences in wind speed and direction for each level were statistically evaluated. Below 850 m, relative differences in wind speed were about 25%–40% during the simulation period (30 h); wind direction differences generally ranged from 6° to 20°. Wind speeds on roughly 80% or more of the model grid points were within a factor of 2 of those from the reference wind fields. The diagnosed winds seem reasonable overall, given the limitations of the CALMET model. In addition, we found that differences between CALMET winds and the reference winds were dependent on time and individual local areas within the domain. Therefore, users need to recognize that CALMET results will be more uncertain for areas that are not close to any observations or if there are strongly varying local winds. The differences were smaller after the lake breeze swept the whole domain than before. Spatially, CALMET can generally produce better surface wind fields compared with the reference winds far behind the front. For the areas near the front, more stations (than NWS stations) are needed to measure highly variable wind fields. Since no upper-air station exists within the CALMET domain under study, the wind direction difference and relative wind speed difference were as large as 100° and 200% above 850 m, respectively. As compared with the success of diagnosing the horizontal wind, the vertical velocity was not well reproduced, which is consistent with results reported elsewhere in the literature.

We also compared the effects of the selection of datasets and model options on CALMET wind fields. For surface winds, CALMET was more sensitive to datasets used than model options. In general, using the lake-breeze option does not significantly improve surface winds, although surface winds could be improved in some areas over land after front passage during the development period of the lake breeze. Adding observations from more stations is an effective way to improve the wind simulation. This is particularly the case if stations are added at locations relatively isolated from other measurements, because the distribution of stations is as important as the number of stations. Trajectory analyses suggest that the lack of observations in some areas can lead to large differences in the vertical velocity is not considered in the trajectory calculation in this case.
tion of observations affect wind field calculations, as one might expect. Adding sodar profile data can improve the wind simulation at lower levels above the surface, particularly when winds were relatively uniform in space over the domain. When spatial variability in winds was large in the domain, using data from more surface sampling locations improved results above the surface more than the addition of a single sodar profile. We did not test the addition of multiple sodars, but we believe that wind field simulations above the surface could be further improved if sodar profile data were available from multiple locations.

5. Suggestions

We have the following suggestions for using CALMET in the many regions that experience complicated mesoscale flows:

1) The default values of BIAS are likely not the most effective choice for complex wind fields. The best BIAS values leading to the smallest differences between CALMET results and the reference data may vary with time (because of temporal changes in wind fields). However, it is not practical for the current version of CALMET to select time-varying BIAS values that provide the minimum possible difference at every sample time. Modification of the CALMET model to accommodate this could be very useful in some situations. Optimal BIAS values will also be region dependent, because the characteristics of mesoscale flows are determined by local terrain and surface features. Because the largest differences occur when the horizontal variability of the wind field is largest, we recommend that users identify periods that typify these conditions for a particular region and tune the BIAS settings for those sample conditions. Weights selected in this manner will have a high likelihood of also providing good results when simpler flows affect the area.

2) For winds under complex conditions, it is important to characterize spatial variability of the wind field because the accuracy of CALMET winds depends on where the area of interest is located within the domain. For example, in this lake-breeze case, differences between CALMET results and the reference data may vary sharply before, after, and during front passage.

3) Using data from more stations generally improves the fidelity of the overall wind field, because CALMET is basically an interpolation- and extrapolation-based model unless in regions of complex terrain. If additional stations are added in such a way, however, as to reduce the ISD, it is possible that winds at some individual grid points may become less accurate. Stations should generally be added in such a way as to increase the ISD.

4) Using sodar data or comparable low-level wind profile information can improve the diagnosed wind field below 500 m at most locations provided the spatial variability is not strong. In the presence of strong spatial variability, additional surface measurements that cover data gaps in the horizontal were found to improve diagnosed low-level winds above the surface more than the addition of a single sodar. In this latter case of stronger variability, sodar data from multiple locations would likely help if resources are available to deploy them. In any case, it is helpful to have at least one upper-air station in the studied domain.

To conclude, CALMET is a useful tool for estimating horizontal wind fields under conditions of significant spatial and temporal variability. The model is likely to perform best when observation sites are sufficiently numerous to resolve characteristic local flows and when the model has been tuned to optimally combine available upper-air and surface measurements for a given region. Without a very high density of surface and upper-air observations, however, it seems unlikely that the model will be very successful in reproducing the vertical wind field. In addition, model parameters in the CALMET may also need to be tuned for each area in which CALMET is applied, because the selection of the parameters may depend on the local wind characteristics. Overall, CALMET seems to be quite capable of providing winds necessary for dispersion modeling in complicated environments. However, one must be aware of the spatial and temporal changes in the differences between CALMET winds and the reference winds. It should be mentioned that a limitation of employing diagnostic models is the lack of lead time. Results can be improved with more frequent observations or with input from advanced prognostic model products (Chandrasekar et al. 2003; Jackson et al. 2006). This way, decisions based on the interpretation of the model results can be made with more confidence.

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APPENDIX

Statistical Measures

Measures of the distribution of meteorological sampling stations are calculated as follows: we assume that all surface stations have the same influence radius. The MD between adjacent (nearest) stations is used to describe station separation in the domain. In practice, one can readily find the shortest distance from each station to all other stations, and hence the median value of adjacent station distances for all stations. The ISD is used to compare how uniformly the stations from different networks are distributed in a given domain. A higher ISD value usually suggests that stations are more uniformly distributed. We use the following straightforward method to estimate ISD: we divide the entire domain into small square cells with a size of MD starting from the farthest southwestern point of the domain. Then we count the number of cells in which at least one station is located. The fractional number of such cells is used to characterize ISD. For example, for the given domain (100 km × 100 km) in this study, MD values are 5, 15, and 18 km for datasets NWS_MESO, NWS, and NWS_PLUS (Table 2), respectively; the total square cell numbers are 400, 48, and 36, respectively; and the numbers of cells where stations are located are 39, 8, and 12, respectively. Therefore, ISD values are about 0.1, 0.16, and 0.33 for the three datasets, respectively. According to this algorithm, stations in the NWS_PLUS dataset are the most uniformly distributed, with stations in the NWS_MESO dataset being the least uniformly distributed. Note that a dataset with stations being more widely separated does not necessarily result in a higher ISD. MD is independent of domain size while ISD is dependent on both MD and domain size. While there may be other ways to quantify ISD, our method is effective. For some extreme cases, our algorithm may not be able to distinguish networks in terms of how closely and uniformly the stations are distributed.

For the calculation of variables used to describe how well the CALMET wind fields approximate those of the reference fields, individual statistical measures are calculated across all grid points in the domain for each analysis time. The variations of these quantities over time are then used to develop their distributions from which medians and quartiles are calculated.

Root-mean-square of the vector wind difference between simulated and observed winds is computed as (Stauffer et al. 1991)

\[
\text{RMS VWD} = \left( \frac{1}{N} \sum_{i=1}^{N} \left( (u_i - u_{0i})^2 + (v_i - v_{0i})^2 \right) \right)^{1/2},
\]

where \((u_i, v_i)\) and \((u_{0i}, v_{0i})\) are the simulated (CALMET) and “observed” (MM5–FDDA) horizontal wind components at the \(i\)th grid, respectively, and \(N\) is the total number of grid points. A mean absolute difference and relative MAD are given by

\[
\text{MAD} = \frac{N}{\sum_{i=1}^{N}} (|V_i - V_{0i}| / N),
\]

and

\[
\text{relative MAD} = \frac{\text{MAD}}{V_0},
\]

respectively, where \(V_i\) and \(V_{0i}\) are the \(i\)th simulated and observed wind speeds, and \(V_0\) is the mean observed wind speed.

Another measure used to determine the accuracy of the simulated wind speed is given by calculating the index of agreement (Willmott 1982; Willmott et al. 1985),

\[
\text{AI} = 1 - \frac{N \langle \text{RMSW} \rangle^2}{\sum_{i=1}^{N} (|V_{mi} - M_0| + |V_{0i} - M_0|)^2},
\]

where \(V_{mi}\) and \(V_{0i}\) are modeled and observed wind speeds at each grid, and \(M_0\) is the mean observed wind speed at all grids. RMSW is the RMS difference of modeled and observed wind speed. The AI can vary between 0 and 1, with 1 representing a perfect agreement of wind speeds at all grid points. This relative and bounded statistic measures how well the variability in the model simulations matches that in the observed data. In mesoscale model applications, a value of AI greater than 0.5 is considered to be typical for a successful simulation of wind speed (Lyons et al. 1995; Seaman et al. 1995; Shafran et al. 2000).

REFERENCES


Cox, R. M., J. Sontowski, and C. M. Dougherty, 2005: An evalu-


