Simulation of a Recent Regional Windblown Dust Event on the Columbia Plateau

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ABSTRACT

A regional, windblown dust modeling system, developed for the Columbia Plateau PM_{10} Program (CP^3), was employed to simulate a regional dust storm that occurred during Sept 23 - 25, 1999. Observed hourly PM_{10} concentrations exceeded 1000 ug m^{-3} at downwind urban receptors and extremely poor visibility due to blowing dust in northeastern Oregon caused a fifty car pile-up with the loss of seven lives. To simulate the emission of PM_{10} due to windblown soil erosion, a detailed emission model has been developed for the CP^3 region. However, in initial applications of the model to historical dust events, the model significantly underestimated observed PM_{10} concentrations, and a calibrated emission constant was required to yield agreement between observed and predicted PM_{10} concentrations. For the 1999 event, new analyses of the dust content of CP^3 soils were incorporated into the emission model. Results from the simulation showed that the predicted PM_{10} concentrations in Spokane, WA were in relatively good agreement (within 30%) with the observed concentrations in terms of the onset and magnitude of elevated concentrations. This good agreement did not require any adjustment of the emission model. However, in Kennewick, WA the predicted concentrations were significantly higher (by a factor of three or more) than the observed concentrations. To investigate the source areas responsible for the PM_{10} predicted for Spokane and Kennewick, a novel back trajectory source footprint method was employed. This technique indicates that during high wind speeds accompanying a dust storm, emissions affecting the urban receptors are within approximately 40 km of the receptor.

INTRODUCTION

Windblown dust can cause severe degradation of local visibility, affect air quality and PM_{10} concentrations on a regional scale, and modify the radiation budget on a global scale. The common denominator in each of these areas is the need for an accurate description of the onset and rate of soil movement and dust production. Early soil erosion studies were concerned with the horizontal movement of soil and the impact on agricultural productivity. More recently, these efforts have expanded to address the production of dust (typically classified as particles smaller than 10 μm diameter) that is transported vertically into the atmospheric boundary layer where it can travel long distances from the source area. Further, mineral dust is an important component of the earth's radiation budget, and recent studies have suggested that mineral dust may contribute to global atmospheric cooling, at least over oceans where satellite images can clearly differentiate between airborne dust and the underlying surface (Hsu et al., 2000; Sokolik and Toon, 1999; Tegan et al., 1996). Diaz et al. (2000) point out that mineral aerosols play an uncertain role with respect to scattering of ultraviolet radiation and show that the actual effect depends upon the form and magnitude of the vertical distribution of mineral dust in the atmosphere.

Guelle et al (2000) employed a global transport model to simulate long term patterns of mineral dust produced in the Saharan region of Africa. They incorporated a dust production model from Marticorena and Bergametti (1995) that accounts for the size distribution of loose soil particles and the landcover surface roughness to determine threshold friction velocities.

In Greenland, analysis of ice cores for dust content can be used to help interpret hemispheric historical temperatures derived from stable isotopic data from ice cores. Tegan and Rind (2000) simulated the relationship between Asia dust sources and dust deposition in Greenland in a series of numerical experiments to investigate how the latitudinal temperature gradient might affect the dust record in ice cores for past climate regimes. Their global model treats four dust size classes: 0.1 – 1, 1 – 2, 2 – 4, and 4 – 8 μm. The dust production scheme was based on Gillette's early work on threshold wind velocity (u_t) that yields dust emission rates using

$$F_d = C(u-u_t)u^2 \qquad (1)$$

where u is the velocity measured at a reference height (usually 10 m) and C is an empirical constant taken to equal 2 $\mu g\ s^2\ m^{-5}$ for clay particles (<1 μm) and 5 $\mu g\ s^2\ m^{-5}$ for silt particles (1 to 8 μm). To match results from a finer scale regional model, Tegan and Rind chose to adjust threshold velocities by grid cell within a range from 4 to 10 $m\ s^{-1}$.

In these dust flux models, the primary mechanism for dust onset is saltation which refers to the hopping motion of particles due to aerodynamic forcing by the wind and the resulting abrasive impact of hopping particles that produce new airborne particles. The threshold velocity or the corresponding threshold friction velocity is defined as the wind speed where visual movement of soil particles can be observed. Loosmore and Hunt (2000) identify the potential for direct suspension of loose dust particles by the wind in a manner such that there is no threshold velocity. Based on a series of wind tunnel experiments using a bed of fine (5 μm) particles, these authors found that the non-abrasive flux followed the relationship:

$$F_d = 3.6u_*^3. \ \ (\text{in } \mu g\ m^{-2}\ s^{-1}) \qquad (2)$$

This yields continuous dust emission for all wind speeds, although the fluxes are very small for higher wind speeds where the saltation mechanism represented by (1) becomes effective.

Wang et al. (2000) designed a dust production scheme aimed at treating source regions in East Asia where the soil characteristics and hydrology are significantly different from sands undergoing erosion in the Sahara and Australian deserts. These authors found that surface friction velocity, relative humidity, and the dominant synoptic weather pattern were the best predictors for the occurrence of large scale dust events. The emission algorithm was given as:

$$Q_{i,j,l} = C_1C_2u_{*i,j,l}(u_{*i,j,l} - u_{*ti,j,l})\ W_{i,j,l}\ R_{i,j,l} \qquad (3)$$

where C_1 is a weighting factor for different land cover types (=180 for grassland, =1200 for Loess Plateau, =1600 for desert), C_2 is an empirical constant (=2.9 x 10^{-11}), $u_{*i,j,l}$ is the friction velocity for location i,j and particle size l, $u_{*ti,j,l}$ is the threshold friction velocity, $W_{i,j,l}$ is a humidity factor (=1 for relative humidity < 40%, = 0 for higher humidities), and $R_{i,j,l}$ is the fraction of particle size l obtained from measurements of suspended dust in the source area.

Part of the interest in Asia dust sources is the recent appreciation for the occurrence of long range transport of Asian pollutants across the Pacific into the continental U.S. (Yienger et al. 2000; Jacob et al., 1999). An example of this Kosa event occurred during April, 1998 when a large regional dust storm in China produced a distinct plume of dust traveling across the Pacific and clearly detected in various ways in the Pacific Northwest (Vaughan et al., 2001).

This type of long range transport is of interest because of the large scale nature of the phenomena and because the import of pollutants from Asia provides a measurable background that must be considered in evaluation of air quality issues along the Pacific rim of the U.S. In eastern Washington, northern Oregon, and northern Idaho, there is ongoing concern with potential exceedances of the National Ambient Air Quality Standard for PM_{10} due to agricultural windblown dust as well as agricultural field burning. As a result of this concern, the Columbia Plateau PM_{10} Program (CP^3) was initiated to determine the character of regional dust storms and to identify new farming practices to reduce the potential for soil erosion and dust production. The results from CP^3 research have helped in the formulation of a natural events policy for the region related to PM_{10} exceedances during high wind events. An important tool used for this purpose is a regional air quality model for windblown dust developed by Claiborn et al. (1998).

In the initial application of the regional model, a form of Gillette's saltation emission model was used with detailed landuse and soil cover data for the CP^3 region. Results from two episodes showed that the empirical dust constant (similar to C in eq. 1 above) had to be adjusted to yield PM_{10} concentrations in agreement with observations. More recently, Lee (1998) modeled five CP^3 dust storms and incorporated a much more detailed emission model described by Saxton et al. (2000) that is based upon detailed field measurements of dust events coupled with portable wind tunnel tests conducted over each of the dominant erodible soils in the region. However, even in this case, the dust algorithm was used with an emission constant that was adjusted from event to event in order to match predicted and observed PM_{10} concentrations. Lee (1998) also conducted a parametric Monte Carlo uncertainty analysis of the input winds and emission model. She found that uncertainties in wind speed and uncertainties in the parameters in the emission did not fully explain the level of adjustment required in the dust emission constant.

Recently, another large dust storm occurred in the CP^3 region in September 1999. This storm reduced visibility in some locations to essentially zero and caused a fifty-car pile-up, which resulted in seven deaths, on Interstate 84 near Hermiston, Oregon. During this event, PM_{10} data were available from monitors in Spokane, WA located in the northeast portion of the domain and in Kennewick, WA located in the south-central portion of the domain. For this event, we have revised the emission model to include a new analysis of the fraction of suspendable soils as a function of soil type within the CP^3 domain. We have also employed archived numerical forecasts of winds obtained with the Mesoscale Meteorological Model Version 5 (MM5) operated by Mass and colleagues (Mass and Kuo, 1997). Results from the simulation of this event are presented in this paper. Our intent is to investigate the impact of the revised emission parameters upon model performance for this type of regional dust storm and to characterize the nature of this wind event.

CP^3 DOMAIN

The Columbia Plateau extends from the Cascade Mountains east to the Idaho Bitterroot Mountains and from the Canadian border into northeastern Oregon. The climate throughout this region is arid, with moist winters and dry hot summers. The annual precipitation on the Plateau ranges from 10 mm yr^{-1} on the western edge to 80 mm yr^{-1} at the Idaho -Washington border (Claiborn et al., 1998). Land use in this region is primarily agricultural with irrigated farming in the west and dryland farming in the east. The soils in this region primarily consist of volcanic ash and loess that have been deposited over a basalt base. These fine soils are very susceptible to wind erosion. Annual soil losses due to wind erosion from unprotected areas on the Columbia Plateau can be as high as 5 cm or 670 metric tons ha^{-1} (Lee, 1998).

Late summer and early fall is harvest season for both irrigated and dryland crops. Therefore, by mid-fall most soils in the region are dry and bare or sparse with vegetative cover. Due to the climate, the rangelands are also dry with pockets of grasses and shrubs, resulting in a vast area on the Plateau with exposed soils highly susceptible to erosion. Four land uses were assumed to be vulnerable to wind erosion: rangeland, land under the Conservation Reserve Program (CRP, land taken out of agricultural production), irrigated agricultural land, and dry cropland. For the dry cropland in the central part of the basin where the rainfall is lowest, it is assumed that a fraction of the land is in fallow, where the fraction is assigned as a function of soil type to reflect known farming practices.

MODELING SYSTEM

The CP^3 regional air quality modeling system consists of the MM5 prognostic meteorological model (Dudhia et al., 1994), the CALMET diagnostic wind field model (Scire et al., 1995), a dust emission model called EMIT, and the CALGRID atmospheric transport model. For this episode, MM5 results were obtained from the operational forecast system at the University of Washington with 12 km x 12 km horizontal grid cell resolution and 33 vertical model layers. A description of the MM5 forecast system is available at http://www.atmos.washington.edu. The CALMET and CALGRID (Yamartino et al., 1992) models use 4 x 4 km horizontal square grids (100 x 85 cells) and ten vertical layers with variable spacing heights of 20, 100, 500, 750, 1000, 1250, 2000, 2250, 2500, and 3000 m, while the EMIT module uses 1 km x 1 km grid cells to account for as much detail as possible in the land use and soil type characteristics. The horizontal winds from MM5 were interpolated with available observations using CALMET, and 3-d wind fields and associated boundary layer parameters were produced at a 4 km grid resolution. The predicted wind speeds were used in the EMIT model (described below) to predict dust fluxes at a 1 km grid resolution which were then summed to 4 km x 4 km grids for use in CALGRID. The CALGRID model, originally developed for photochemical simulations, solves the K-theory form of the atmospheric diffusion equation (Yamartino et al., 1992). We employed CALGRID with no chemistry and treated suspendable dust (PM_{10}) as an inert species with a deposition velocity of 0.1 cm s^{-1}.

In the EMIT model, horizontal soil movement is predicted from available wind energy, and vertical flux of PM_{10} is calculated as a function of the horizontal dust flux. The prediction of horizontal soil flux is similar to the wind erosion equation (WEQ) (Woodruff and Siddoway, 1965) and is based on the wind energy, soil erodibility, percent surface cover, surface roughness and soil moisture. As described by Saxton et al.(2000) the relationship between these variables was determined as a series of multipliers:

$$Q_t = W_t*EI*(e^{-0.05*SC} \times e^{-1.32*K})*WC \quad (4)$$

where Q_t is the horizontal soil flux (kg m^{-1}), $W_t = (U^2(U-U_t))*60$ is wind energy (m^3 s^{-3} per hour of the event), $EI = 0.06*(ER)^{0.6}$ is soil erodibility (g s^3 m^{-3}), WC is soil water content (non-dimensional term with range 0 – 1), SC is vegetative surface cover (%), K is the random roughness of large soil elements (cm), and ER is relative erodibility index (non-dimensional). This equation predicts the mass of soil transported horizontally from an eroding field for a width of 1 m, a height of 1.5 m, and for a time period of one hour (Saxton et al., 2000). The vertical flux of PM_{10} ($g\ m^{-2}\ s^{-1}$) during an erosive period is a function of the horizontal flux, soil dustiness, wind velocity, and a calibrated dust constant:

$$F_d = K_d*C_v*U^2*Q_t*(D/100) \qquad (5)$$

where K_d is a calibrated dust constant (non-dimensional), C_v is a units conversion factor, U is the wind velocity ($m\ s^{-1}$) at 3 m height, and D is the soil dustiness (fraction of PM_{10} in soil). Soil dustiness is the potential of the soil to produce PM_{10} and is dependent on the type of soil. Based on recent wind tunnel studies (Thompson, 2000), the soil dustiness constant used in the EMIT model were revised from initial values used by Lee (1998).

PRESENTATION AND DISCUSSION OF RESULTS

The 1999 dust storm was due to high winds that actually extended over three days as shown in Figure 1. On September 23, 1999, wind speeds in Spokane reached a maximum of approximately 12 $m\ s^{-1}$ in mid-afternoon. A second period of high winds with a peak of 9 $m\ s^{-1}$ occurred during mid-day on September 24, and the highest wind speeds exceeding 14 $m\ s^{-1}$ were reached in a third period at mid-morning on September 25. It should be noted that the threshold velocity in EMIT is fixed at 6.6 $m\ s^{-1}$ at 10 m height. A similar pattern in wind speed was observed at the Pasco station near Kennewick, WA. Figure 1 also shows the predicted winds obtained from the 12 km resolution MM5 forecasts and the interpolated 4 km resolution CALMET winds. In general, the MM5 winds are less than the observed winds, while the interpolated wind speeds from CALMET are in very close agreement, as we would expect, with the observations. Comparison of the model winds and observations are summarized in Table 1. For wind direction, both models yield relatively good agreement with observations as shown in Figure 2.

Table 1. Summary of wind speed comparisons for MM5 and CALMET versus observations for Spokane and Pasco, WA.

WS (m/s) for Spokane					
	Ave.	Min.	Peak	Time of Peak (DDHH)	R^2
Observations	7.1	1.5	15.4	2510	
CALMET	6.7	2.3	14.8	2510	0.95
MM5	4.1	1.3	9.3	2509	0.49
WS (m/s) for Pasco					
	Ave.	Min.	Peak	Time of Peak (DDHH)	R^2
Observations	5.5	1.5	12.9	2505	
CALMET	5.0	0.2	12.4	2505	0.99
MM5	2.8	0.5	6.3	2513	0.42

As a result of the high wind speeds that occurred during this fall period, elevated concentrations of PM_{10} were predicted for a large portion of the CP^3 domain as shown in Figure 3. This map of surface

PM_{10} concentrations corresponds to the hour of the car pile-up at 1000 on Sept 25. There are large portions of the domain with concentrations well above 1000 ug m^{-3}. This widespread plume of PM_{10} extending across the Columbia Plateau is characteristic of all of the dust storms we have simulated (Claiborn et al., 1998; Lee, 1999).

PM_{10} Tapered Element Oscillating Microbalance (TEOM) hourly data show that elevated concentrations of PM_{10} were observed in Spokane and Kennewick on both Sept 23 and Sept 25. Time series of the observations are shown in Figures 4 and 5. During Sept 23, peak PM_{10} hourly concentrations reached approximately 500 ug m^{-3} in Spokane and were as high as 2000 ug m^{-3} in Kennewick. We also note that Claiborn et al. (2000) found that $PM_{2.5}$ accounts for 30% of PM_{10} during these kind of dust storms. Predicted hourly PM_{10} concentrations also showed elevated levels in Spokane, but the maximum predicted concentration was approximately half the observed level and the predicted maximum occurred several hours earlier compared to the observations. In Kennewick, the peak model prediction was considerably less than observed, although the timing of the peak was within one hour of observed. Significant elevation of PM_{10} concentrations was not observed or predicted in either Spokane or Kennewick during Sept 24.

On Sept 25 when the winds were the highest, both the maximum observed and predicted concentrations exceeded 1000 ug m^{-3} in Spokane. In this case, the predicted PM_{10} concentrations reached a maximum value at the beginning of the high wind period and concentrations remained elevated for approximately 10 hours. The onset of high observed concentrations occurred at the same time as predicted, although the maximum observed concentration occurred several hours after the predicted maximum. The observed concentrations also decreased to background levels several hours before the predicted concentrations began to exhibit a drop toward the background level. In Kennewick, the observed concentrations varied between 500 and 1000 ug m^{-3} for approximately 13 hours on Sept 25. This pattern was matched by the predictions, although the onset of elevated concentrations began 3 hours earlier than observed and the maximum predicted concentration was approximately six times higher than the observed maximum. There was good agreement between observations and predictions in the timing of the decrease of concentrations to background levels at Kennewick.

For periods when the observed concentrations exceeded 80 ug m^{-3}, the model predictions, in general, showed reasonably good agreement with observations in Spokane, but were approximately three times higher than observed on average and the maximum concentration was six times higher than observed in Kennewick as shown in Table 2.

Table 2. Summary of observed and predicted hourly PM_{10} concentrations in Spokane and Kennewick.

Spokane	Observed	Predicted	P/O	Kennewick	Observed	Predicted	P/O
Mean	400	279	0.7	Mean	630	1988	3.2
Std	397	496	1.2	Std	491	2929	6.0
Max	1483	1943	1.3	Max	1731	10192	5.9

To further investigate the model predictions, we have employed a back-trajectory source footprint method as describe by Napelenok et al. (2000). In this approach, the CALMET winds are reversed in direction and inverted in time. These inverted wind fields are then used as input to the CALPUFF dispersion model for a unit source located at the PM_{10} receptor of interest (Spokane or Kennewick). The resulting concentration field obtained with the reverse CALPUFF simulation actually maps out the probability distribution for a source to impact the receptor. In turn, this map of probability distribution can be combined with the underlying gridded emission fields from EMIT to yield a map of the fractional contribution of emissions to the concentration observed at the receptor at a specified time. The result of this source-footprint calculation is shown in Figure 7 for receptors in Spokane and Kennewick at 1000 on Sept 25. For Spokane, the extent of the source footprint is approximately 10 grids cells upwind (40 km) and this area encompasses approximately 98% of the emissions contributing to concentrations at the receptor. More than 60% of the contribution is due to emissions within 20 km of the receptor. This result has potential implications for efforts to manage farm practices to protect air quality in the populated urban areas. Further work is required to examine source footprints for a number of different dust storms and to examine the effects on receptor concentrations due to changes in emissions in the zone immediately upwind of the receptor.

SUMMARY AND CONCLUSIONS

The CP^3 windblown dust modeling system was modified to incorporate new analyses of soil dust content for CP^3 soils. With this modification, the modeling system was used to simulate a recent regional dust storm that occurred during Sept 23 - 25, 1999 when observed PM_{10} concentrations exceeded 1000 ug m^{-3} at urban receptors and a 50 car pile-up with seven fatalities occurred on a freeway in agricultural lands. The modeling system showed relatively good agreement with observations in terms of the onset of elevated concentrations and the magnitude of concentrations at the Spokane monitoring site. In Kennewick, the observed pattern of elevated concentrations was qualitatively matched by the predictions, although the onset of elevated concentrations began 3 hours earlier than observed and the maximum predicted concentration was approximately six times higher than the observed maximum. There was good agreement between observations and predictions in the timing of the decrease of concentrations to background levels at Kennewick. In terms of mean elevated concentrations, the model agreed to within 30% of observations in Spokane, but was higher by a factor of three compared to observations in Kennewick.

Analysis of the source footprint that contributes to receptor concentrations indicates that almost all of the emissions are within 40 km of the receptor during these high wind speed situations. Further work is needed to examine how changes in emissions within the source footprint can change concentrations at a receptor.

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Figure 1. Observed and predicted (MM5 and CALMET) wind speeds at Spokane for September 23 - 25, 1999.

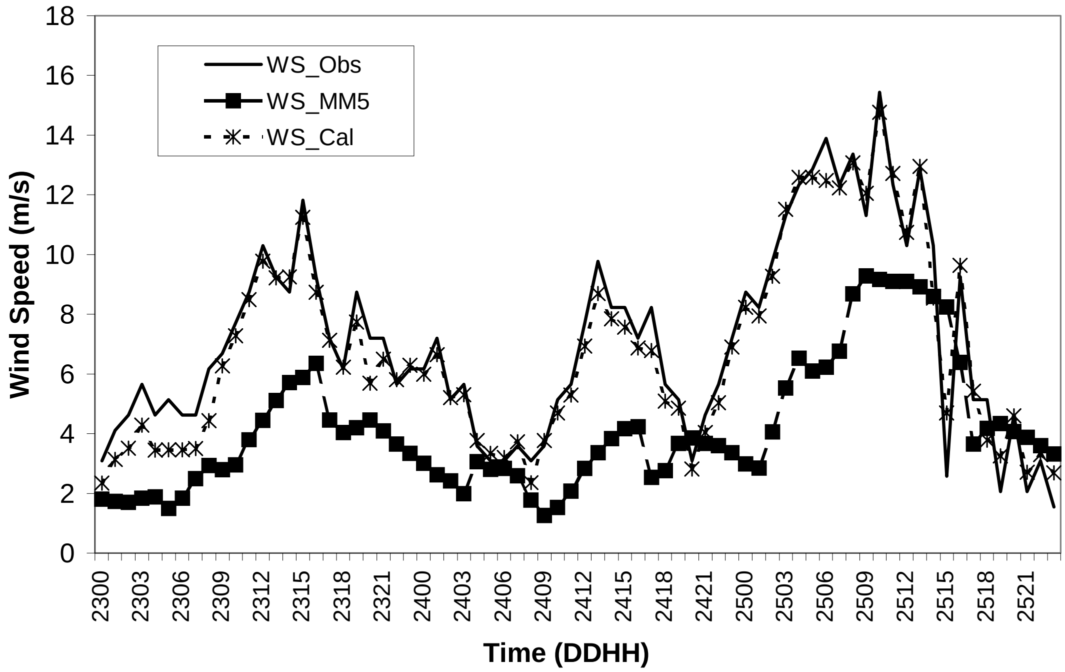


Figure 2. Observed and predicted wind directions (MM5 and CALMET) for Spokane during September 23- 25, 1999.

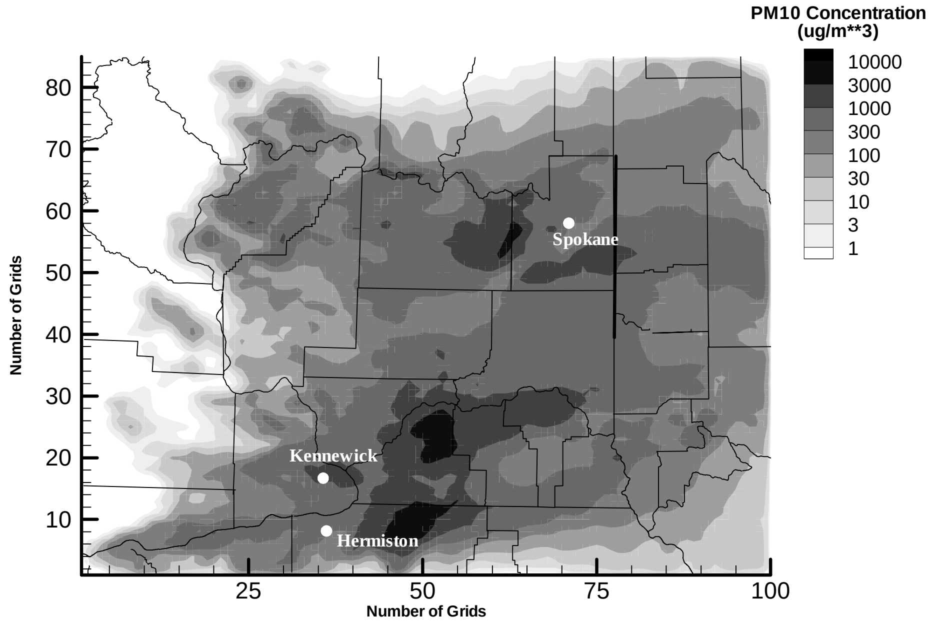


Figure 3. Predicted surface concentrations of PM_{10} for 1000 on Sept. 25, 1999.

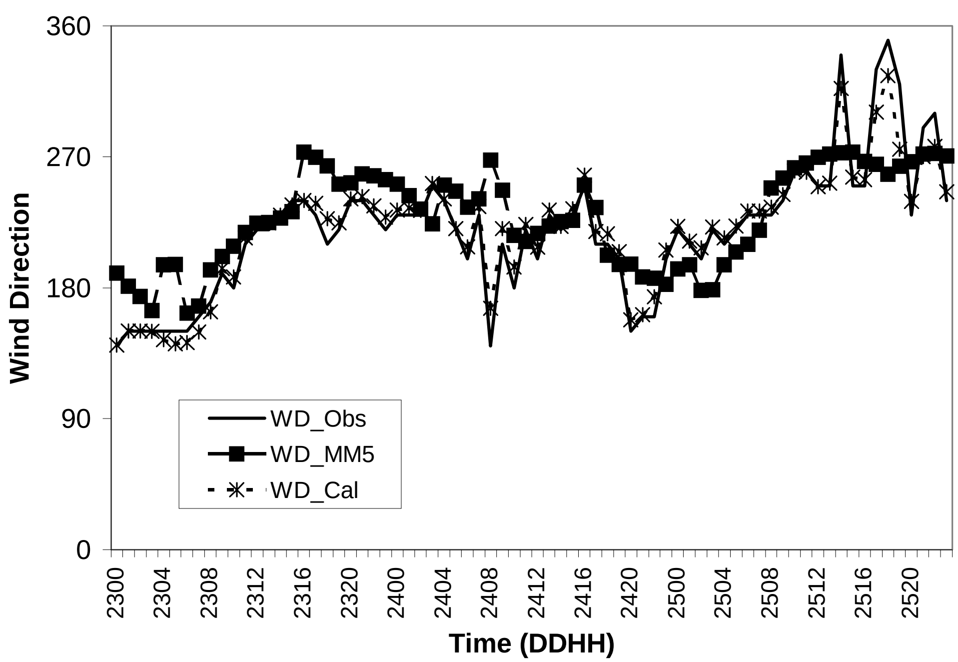


Figure 4. Observed and predicted ambient PM_{10} concentrations in Spokane during Sept 23 - 25, 1999.

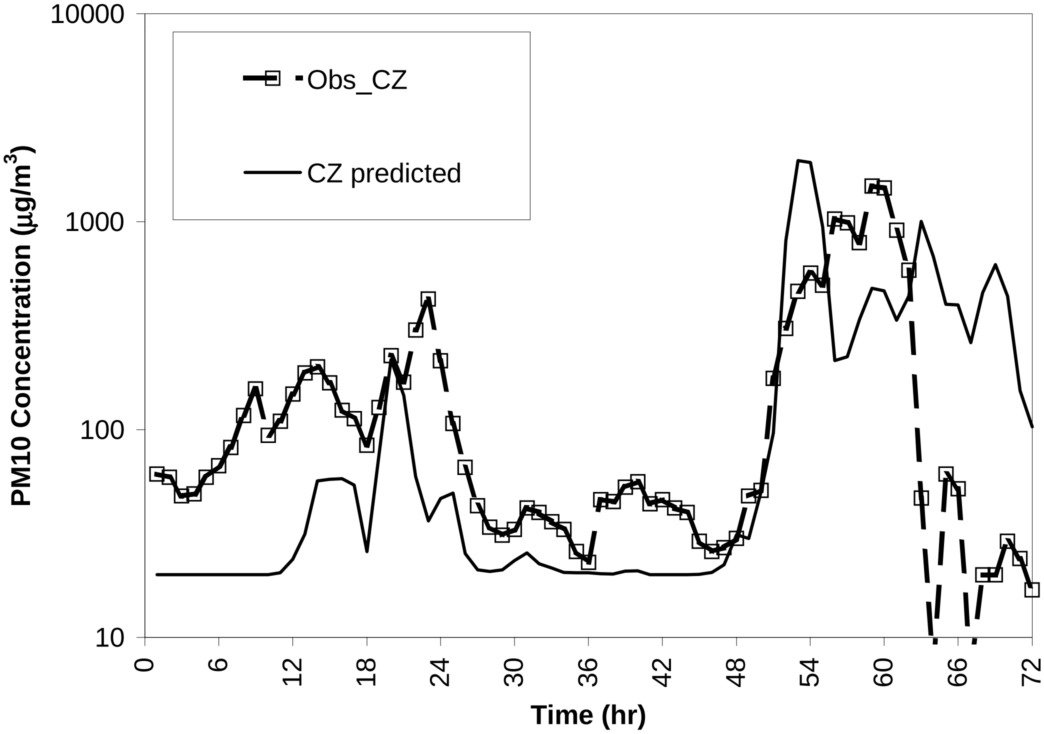


Figure 5. Observed and predicted ambient PM_{10} concentrations for Kennewick, WA during Sept 23 - 25, 1999.

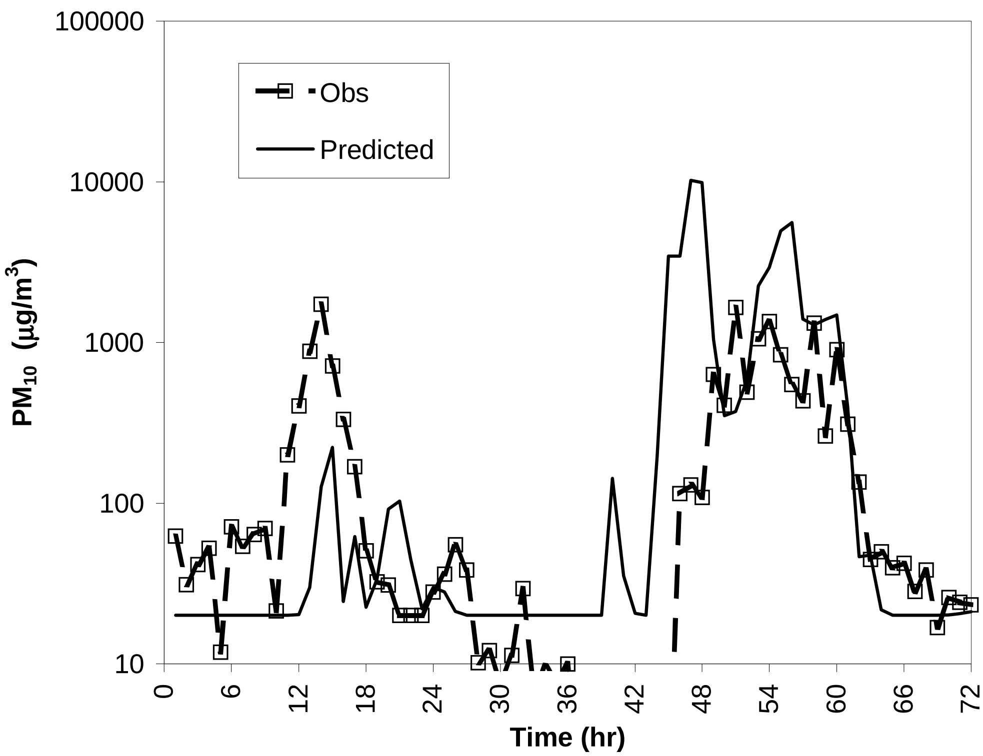


Figure 6. Map of windblown dust emissions (g/grid cell/s) for 1000 on Sept. 25, 1999.

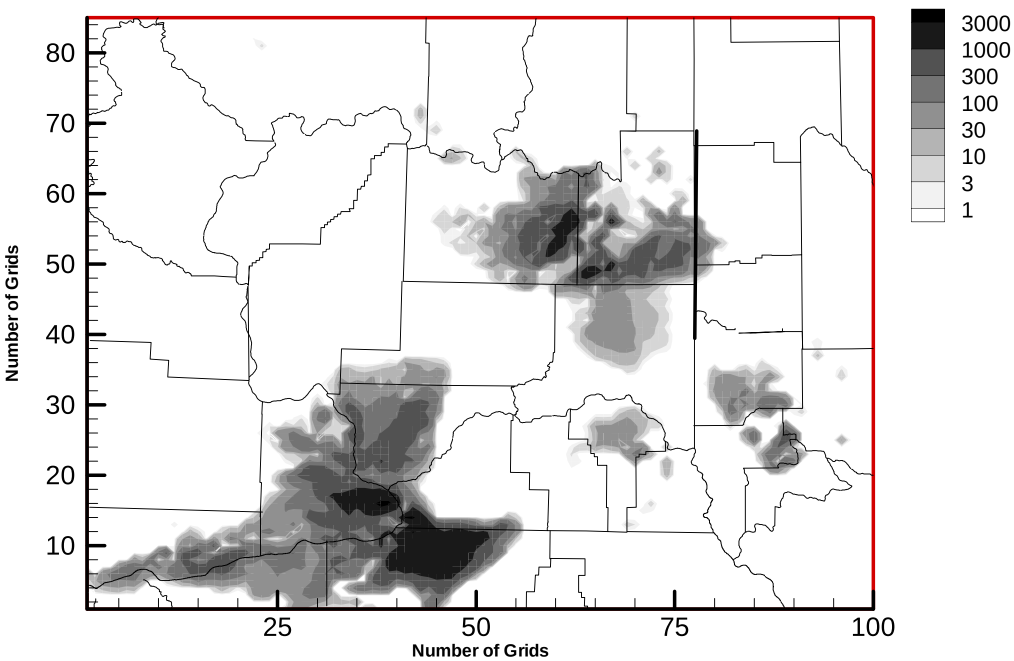
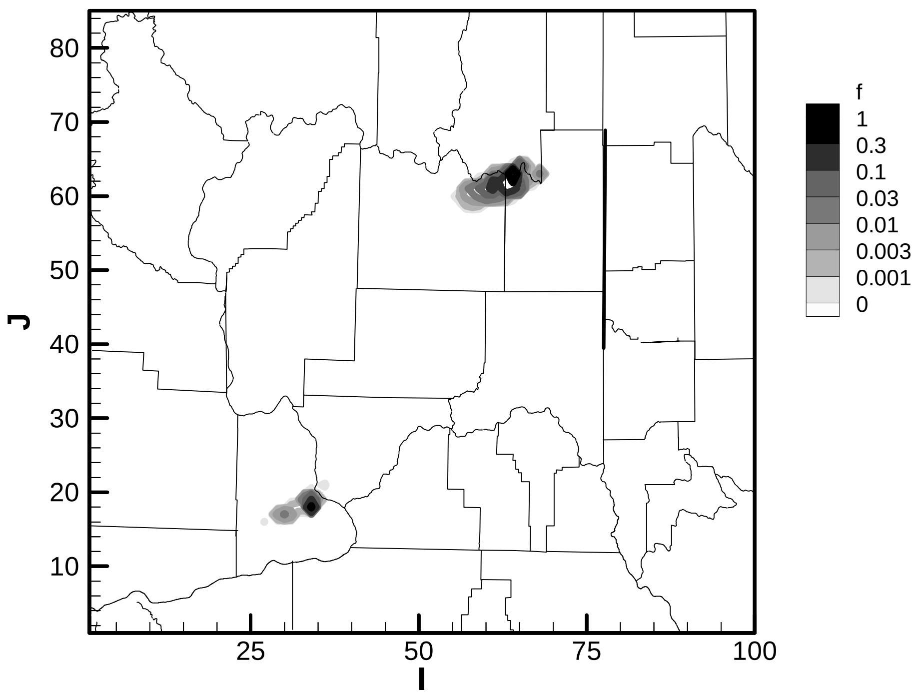


Figure 7. Fractional contribution of windblown dust emissions to concentrations observed at Spokane (upper right) and Kennewick (lower central).



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