

## Regional measurements and modeling of windblown agricultural dust: The Columbia Plateau PM<sub>10</sub> Program

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**Abstract.** The Columbia Plateau PM<sub>10</sub> Program [CP<sup>3</sup>] is a multi-investigator study of windblown dust in the Pacific Northwest with an emphasis upon the role of agricultural lands in regional dust storms. Ambient measurements of PM<sub>10</sub> within the source areas of the central basin of Washington during several autumn dust periods show that typical background concentrations [nonwind-event periods] decrease from an average of 34  $\mu\text{g m}^{-3}$  in early fall to 10  $\mu\text{g m}^{-3}$  in late fall. During wind events, ambient concentrations at downwind urban receptors can exceed 500  $\mu\text{g m}^{-3}$  on an hourly basis, with 24 hour averaged values as high as 300  $\mu\text{g m}^{-3}$ . Particle counts during wind events are enhanced by as much as a factor of 5 for particle sizes greater than 5  $\mu\text{m}$ , and also for sizes between 1 and 5  $\mu\text{m}$  compared to nonwindy periods. Analysis of the synoptic conditions which exist during these dust storms showed a common situation where a surface low is moving rapidly across British Columbia while a surface high is positioned in the Great Basin of Nevada. A regional windblown dust air quality model, developed for the CP<sup>3</sup> study, predicts large dust plumes stretching across eastern Washington with maximum concentrations in the source regions exceeding 10,000  $\mu\text{g m}^{-3}$ . Total mass emissions during a storm are estimated to equal 100 Gg  $\text{dy}^{-1}$ , which represents about 1% of recent estimates of the global annual dust emission rate. In the initial applications of the model, available PM<sub>10</sub> observations are used to calibrate the dust emission algorithm. Changes in the dust constant for two modeled events are consistent with changes in soil cover and accumulated precipitation between an early fall event and a late fall event. The estimated fluxes are in a range similar to those in the literature but appear to be much less than estimated from global modeling of recently disturbed soils.

### 1. Introduction

Wind erosion of soils has long been a concern of the agricultural community, and considerable scientific efforts have been expended to understand the microphysics involved in the onset and production of airborne dust due to wind. More recently, interest in windblown dust has also developed from concerns about soil alkalinity with respect to acid deposition, the need to understand the role of airborne dust in Earth's radiation budget, and the requirement to eliminate dust pollution episodes which have been documented in Washington, California, and other U.S. locations.

Following the Dust Bowl years of the 1930s, *Chepil* [1945a,b, 1951], *Bagnold* [1941], and others investigated the drag and lift forces on grains of soil and provided initial descriptions of soil creep (the movement of grains of soil along the surface) and soil saltation (the bounce of grains into the air) that precede airborne soil transport. This work and additional findings from Fryrear and others [e.g., Fryrear, 1985; Fryrear et al., 1988] were incorporated into an empirical wind erosion equation for use by the U.S. Soil Conservation Service to document the climatological potential for wind erosion of soils [Hagen, 1991]. Recent work by Raupach and coworkers [Shao and Raupach, 1992; Raupach et al., 1993] has concentrated on the fundamental

descriptions of the soil grain saltation process as the first step in understanding soil erosion. These kinds of results have been incorporated into models of the dust emission flux by *Alfaro and Gomes* [1995] and also *Marticorena and Bergametti* [1995].

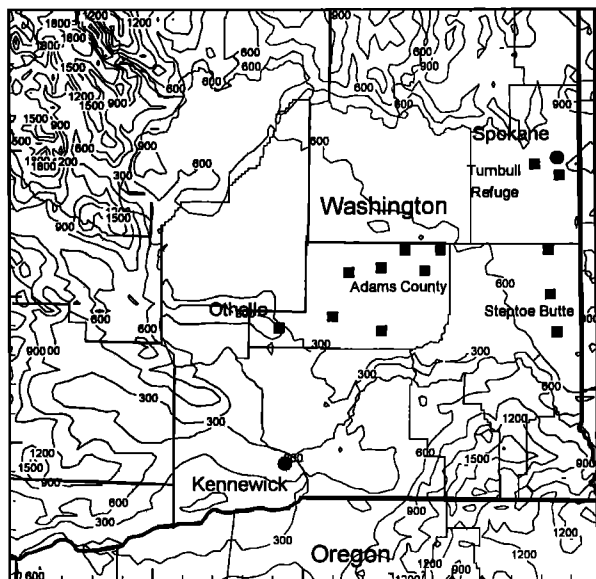
In the 1970s and mid-1980s, windblown dust was recognized as a major source of atmospheric alkalinity, and Gillette and coworkers [Gillette, 1988; Gillette and Passi, 1988; Gillette and Hanson, 1989] developed dust (particulate matter smaller than approximately 20  $\mu\text{m}$ ) emission inventory models as a basis for treating regional contributions of airborne soil material in regional acid deposition/air quality models as part of the National Acid Precipitation Assessment Program (NAPAP) [Placet, 1991].

More recently, the effects of windblown dust upon Earth's radiation budget have also been investigated. Saharan dust storms have been documented using satellite remote sensing [Jankowiak and Tanre, 1992], while Gillette and others conducted an extensive study of windblown dust in the former Soviet Union [Gillette et al., 1993]. These kinds of observations have been incorporated into a global inventory of mineral dust in the atmosphere recently developed by Tegen and Fung [1994, 1995]. In the model described by Tegen and Fung, an empirical dust emission function was coupled with a gridded transport model in order to calculate atmospheric concentrations of dust. These predicted airborne concentrations were then used to calculate the atmospheric optical depth for different regions and seasons.

In the United States, regulations controlling particulate matter smaller than 10  $\mu\text{m}$  in aerodynamic diameter (PM<sub>10</sub>) have

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**Figure 1a.** Digital terrain map of the Columbia Plateau PM<sub>10</sub> Program domain; and locations of PM<sub>10</sub> sampling sites in Adams County, along Highway 195, in Spokane, and in Kennewick.

motivated efforts to understand the role of windblown dust as one of the sources which can cause exceedances of air quality standards. In California, *Reid and Flocchini* [1994] and *Cahill et al.* [1995] have investigated windblown dust events in the dry Owens Lake region of eastern California which cause the 24 hour PM<sub>10</sub> standard of 150  $\mu\text{g m}^{-3}$  to be exceeded several times each year. In Washington state, windblown dust from agricultural areas in the Columbia Plateau of central Washington has led to exceedances of PM<sub>10</sub> standards in Spokane, Kennewick, and Sandpoint.

To better understand the emission and transport of windblown dust in the Columbia Plateau, the multi-investigator Columbia Plateau PM<sub>10</sub> Program (CP<sup>3</sup>) was initiated in 1993. The overall goal of the program is to document the contribution of agricultural windblown dust to ambient particulate matter exceedances in the population centers of eastern Washington and

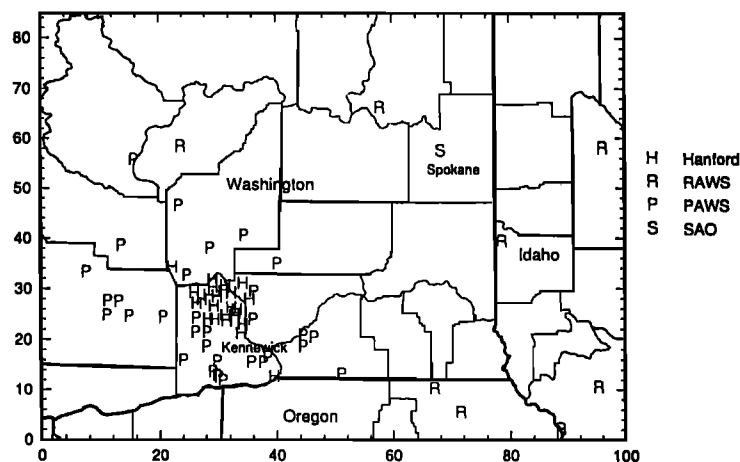
northern Idaho and to develop possible control strategies to decrease the occurrence and extent of windblown dust episodes [Saxton, 1995]. The program consists of a number of objective areas covering (1) remote sensing and mapping of soils, vegetation, and other environmental attributes in the area; (2) measurement and modeling of dust emissions from agricultural and natural soils; (3) measurement of mineral aerosol concentrations during windstorms; (4) development and application of a regional transport and dispersion model for windblown dust; and (5) investigation and development of agricultural practices for control purposes. Findings from this work will also contribute to our understanding of the role of agriculture versus natural lands as sources of mineral dust on regional and global scales.

In this paper, initial results from the CP<sup>3</sup> objectives 3 and 4 are presented. These include (1) ambient particulate measurements that were conducted during nonevent periods; (2) a climatological description of regional windblown dust events; (3) the spatial and temporal concentration distributions during wind events; (4) description of a regional air quality model adapted for windblown mineral aerosol; and (5) illustration of model results for two windblown dust events. A more detailed description of the model and results for a number of dust events is presented in a separate paper (B. Lee et al., manuscript in preparation, 1998).

## 2. Background

The Columbia Plateau, shown in Figure 1(a&b), is bounded by the Blue Mountains to the south, the Columbia River and Cascade Mountains to the west and north, and the Rocky Mountains to the east. Basalt lava flows covered this area at one time, and built up the land form. On top of these basalt layers is a layer of loess, a wind deposited mixture of silt, clay, and some fine sand. This composition, plus the lack of soil organics, makes this a highly erodible soil. The layer of loess is 45 m deep in some places and only a few centimeters deep in others [Campbell, 1962].

The erodibility is further enhanced by an arid climate in central and eastern Washington, where precipitation rates change rapidly from less than 10 mm yr<sup>-1</sup> at the western edge of the Columbia Plateau to more than 80 mm yr<sup>-1</sup> at the Idaho - Washington



**Figure 1b.** Locations of surface and upper air (SAO) meteorological stations used in the wind field model (RAWS refers to Regional Automated Weather Stations operated by the U.S. Forest Service, PAWS refers to Public Agriculture Weather System operated by Washington State University, and Hanford refers to surface weather stations operated by the Hanford Nuclear Reservation).

**Table 1.** Historical Windblown Dust Events and Meteorological Conditions that Lead to High Concentrations of PM<sub>10</sub> in Eastern Washington

Date	Temperature °C	Dew Point °C	Wind Speed m s <sup>-1</sup>	Wind Direction °N	PM <sub>10</sub> µg m <sup>-3</sup>		
					CZ	NZ	KW
November 23, 1990	12 ± 2	3 ± 1	9.4 ± 2.7	190 ± 9	na	251	126
October 21, 1991	11 ± 4	5 ± 4	4.0 ± 3.1	182 ± 51	351	267	1035
September 14, 1992	17 ± 3	9 ± 3	5.8 ± 1.8	261 ± 18	321	na	46
September 12, 1992	14 ± 4	5 ± 2	5.8 ± 1.8	255 ± 17	803	na	58
October 8, 1992	12 ± 4	5 ± 1	3.6 ± 2.2	201 ± 54	185	na	49
September 11, 1993	17 ± 4	4 ± 1	4.9 ± 2.7	249 ± 33	300	255	118
November 3, 1993	11 ± 3	-1 ± 2	6.7 ± 2.7	249 ± 32	207	100	1166

CZ is an industrial site in Spokane, NZ is a residential site in Spokane, and KW is an urban site in Kennewick, WA. Meteorological data are 24 hour averages measured at Othello, WA.

border. There is also a general increase in elevation from 370 m in the center of the plateau [western Adams County] to 900 m in Spokane along the eastern edge of Washington.

Land use in the Columbia Plateau is primarily agricultural. Dryland farming (primarily of wheat) dominates in the east, and irrigated farming prevails in the western portion. Each fall after harvest, the irrigated soils are bare and dry. At the same time, half of the dryland agricultural soils lie bare, since the low amount of moisture dictates a two-year crop rotation that leaves half of the nonirrigated farmland fallow each year. During the summer, the fallow land is cultivated several times for weed control. Seeding takes place in early fall and produces a "dust mulch," a layer of very fine dirt that may be a few centimeters thick. The texture of the dust mulch is airy and powdery, and its purpose is to preserve soil moisture next to the seed. By late fall the fields will have a few centimeters growth of wheat sprouts. As a result, in the fall, both irrigated and fallow fields are bare, and harvested fields contain some vegetative residue. Surrounding rangelands are also very dry in the fall with sparse grasses and shrubs. The end product is an expansive area of mostly bare, dry soil that is highly susceptible to wind erosion, especially during the period from approximately September 1 through the end of November. From 1990 to 1996, there have been 12 exceedances of the PM<sub>10</sub> standard in Spokane which occurred during the windblown dust season in central Washington.

Meteorological and particulate concentration data for seven windblown dust events that occurred from 1990 to 1993 and that

led to high PM<sub>10</sub> levels (over 150 µg m<sup>-3</sup> averaged over a 24 hour period) in Spokane are summarized in Table 1. Meteorological data are from the Othello site in the central basin of Washington.

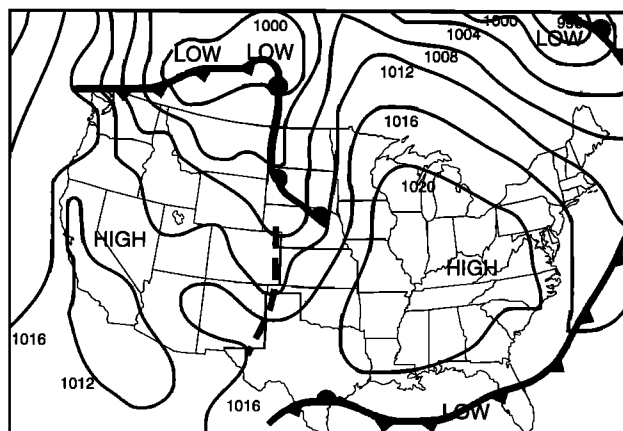
Of these seven events, six have very similar synoptic-scale weather phenomena. For each, the jet stream passes over, or very near, the general region (the surface map for September 4, 1992, does not show this synoptic phenomenon). In addition, these events are characterized by a surface low-pressure system located in the southern half of British Columbia or Alberta, and a surface high-pressure system located in the Southwest United States [e.g., see Figure 2]. The surface low-pressure system located north of the Columbia Plateau generates southwesterly winds in the Columbia Plateau that are enhanced by the clockwise flow of a surface high pressure system located in the Southwest United States. The commonality of this synoptic feature is an important observation for predictions of windblown dust storms in central and eastern Washington state.

### 3. Experimental Methods

Experiments were conducted during the 1993, 1994 and 1995 windblown dust seasons (September 1 to November 30), during which a network of filter samplers was deployed. The goal of the network sampling program was to establish "background" concentrations throughout the source area, during both windy and nonwindy conditions. Additionally, a particle size analyzer was periodically operated during both windy and nonwindy periods, and data from continuous PM<sub>10</sub> analyzers at one rural and two urban locations were collected.

Samplers were deployed at eight sites in Adams County, which represents a portion of the source area (hereafter referred to as the "Adams Co. network"). Adams County lies to the southwest (i.e., upwind) of Spokane and has many erodible soil areas. Each site was located on Conservation Resource Program (CRP) fields that are kept in grasses and thus are not sources for windblown dust. Another series of samplers (representing the downwind area) was deployed along Highway 195 that runs north and south between Pullman and Spokane, along the eastern edge of Washington state. Samplers were also deployed at several elevations on Steptoe Butte (elevation of approximately 300 m above surrounding fields), located in eastern Washington between Spokane and Pullman. In addition, the Spokane County Air Pollution Control Authority (SCAPCA) operates several samplers at sites within the Spokane city limits, and at a site located at the Turnbull National Wildlife Refuge (TNWR) (located south-southwest of Spokane). The locations of these sampling sites are shown in Figure 1a.

Programmable, battery-operated samplers (Airmetrics, Springfield, Oregon) were used to collect filter samples for PM<sub>10</sub>.



**Figure 2.** Surface weather map for September 11, 1993, which exhibits the typical synoptic wind storm pattern with a surface low in British Columbia, the associated cold front sweeping across Washington, and a surface high in Nevada.

The sampler operates at a sample flow rate of 5 L min<sup>-1</sup>. Samples were collected on 47 mm Teflon PTFE membrane and Whatman quartz filters (Gelman Sciences Inc.). Results of experiments in which the Airmetrics low-volume sampler was compared to other samplers have been discussed previously [Kantamaneni *et al.*, 1996]. Most studies that compared the performance of the Airmetrics sampler to other sampling methods were conducted at PM<sub>10</sub> levels below 100 µg m<sup>-3</sup>. To our knowledge, Airmetrics samplers have not been colocated with other PM<sub>10</sub> samplers in areas where the PM<sub>10</sub> exceeds 200 µg m<sup>-3</sup>.

The Airmetrics sampler has a programmable timer; however, the onset of a windblown dust event is unpredictable and often so sudden that, by the time the samplers can be deployed from Pullman throughout Adams County, the momentum of the storm can be lost. Therefore a remote control system for the samplers in the Adams County network was developed. A cellular phone is used in conjunction with a modem and programmable data collection device to enable the user to remotely activate the field-deployed samplers from Pullman.

The ability to leave samplers in the field for a length of time prior to and after operation raises the question of how much passively deposited material will collect on the filter between filter changes. Passive deposition tests were conducted over a 5-week period. The average daily passive deposition rate was found to be  $2 \pm 0.4$  µg d<sup>-1</sup>. For a sampler left in the field for 1 week and then operated for 12 hours, the passive deposition would result in a positive bias of approximately 4 µg m<sup>-3</sup>.

Near real-time PM<sub>10</sub> and PM<sub>2.5</sub> measurements via tapered element oscillating microbalance technology (TEOM, Rupprecht and Patashnik) are collected continuously by SCAPCA in an industrial location (designated CZ) and in a residential location (designated NZ). In addition, during the windblown dust season of 1994, a third TEOM was deployed at the TNWR site. In intercomparisons conducted between the size selective inlet (SSI) filter sampler and the TEOM in Spokane, the TEOM typically reads approximately 5% less than the SSI [Kantamaneni *et al.*, 1996]. Periodically, particle size distributions were measured using a laser aerosol spectrometer (LAS, Particle Measuring Systems).

Filters were gravimetrically analyzed using a microbalance (Cahn model 33) with a 250 mg capacity and a sensitivity of 0.001 mg. The balance was calibrated before each use, and the zero was monitored during weighings. Filters were equilibrated in a chamber at  $40 \pm 5\%$  relative humidity for 24 hours before and after sampling. After removal from the equilibration chamber, the filters were weighed in a room maintained at a temperature of  $20 \pm 5^\circ\text{C}$ . At least three laboratory blanks were weighed with each batch of field filters. Field duplicates were collected in 1993 with colocated samplers at sites 1 and 5 in Adams Co., and in 1994 with colocated samplers located on Steptoe Butte, and at site #6 in Adams Co. Trip blanks were also collected, and reweighs were performed on at least 10% of the filters.

During the 1993 season (September 20 to November 3, 1993) the source region samplers were operated from 0800 to 1800 on an every other day basis for approximately 6 weeks. During the 1994 season (September 20 to October 30, 1994), an abbreviated network was deployed in Adams County (sites 3, 4, 5, and 6), downwind samplers were deployed along the highway between Pullman and Spokane and on Steptoe Butte, and continuous monitors were operated at TNWR. An abbreviated network was also operated in 1995.

## 4. The Regional Windblown PM<sub>10</sub> Air Quality Model

The approach taken in the development of a regional transport and dispersion model for windblown dust in CP<sup>3</sup> was to adapt the existing CALMET/CALGRID modeling system [Scire *et al.*, 1995; Yamartino *et al.*, 1992]. CALMET and CALGRID were originally developed for the state of California to model urban- to regional-scale photochemical oxidant formation; the model is now being used in various formulations to model photochemical oxidants in California and other areas [e.g. Pilinis and Kassomenos, 1993]. To generate dust emissions, a new code (EMIT) was developed which uses CALMET wind and turbulence data to calculate dust fluxes by grid and time step, which are then used as input to the CALGRID transport model.

### 4.1. Wind and Turbulence Modeling

CALMET is a three-dimensional diagnostic meteorological model specifically designed for use in complex terrain. It uses a terrain-following coordinate system and contains a diagnostic wind field generator with a divergence minimization procedure that includes parameterized treatments of slope flows, kinematic terrain effects, and terrain blocking effects. The model also includes a detailed boundary layer module to predict the structure and character of the atmospheric boundary layer in terms of the surface friction velocity, sensible and latent heat fluxes, Monin-Obukhov length, convective velocity scale, and mixing height.

CALMET is designed to use hourly average surface observations of wind speed, wind direction, temperature, cloud cover, ceiling height, surface pressure, relative humidity, and precipitation and twice daily upper air observations of wind speed, wind direction, temperature, and pressure as a function of height. However, CALMET also has the capability to use predicted winds from a prognostic weather model, such as the Mesoscale Meteorological Model [MM4 or MM5] as a way to provide a more dense array of upper air and surface input data. Digital terrain data are required at the specified grid resolution, and land use data are needed to determine surface roughness and Bowen ratio estimates using a look-up table modified for this study.

### 4.2. PM<sub>10</sub> Emission Modeling

Gillette and coworkers, in the development of dust emission models for NAPAP, found from dust flux measurements that the emission flux of dust from soils could be described in terms of a threshold friction velocity ( $u_{*t}$ ) which incorporates the effects of soil type, soil moisture, soil texture, and vegetative cover [Gillette, 1988; Gillette and Passi, 1988; Gillette and Hanson, 1989]. With this empirical function, the flux of dust (g m<sup>-2</sup> s<sup>-1</sup>) due to wind could be described in terms of the existing friction velocity:

$$F = Cu^{*3}a_g[u - u_{*t}] \quad (1)$$

where  $C$  is an empirical dust constant ( $\sim 1 \times 10^{-3}$  g s<sup>3</sup> m<sup>6</sup>) and  $a_g$  ( $\sim 1.20$ ) is a constant to correct for the use of hourly averaged winds compared to the nonlinear effect of near-instantaneous gusts upon dust production. For high wind speeds, this scheme relates the dust flux to the friction velocity raised to the fourth power. Nickling and Gillies [1993] employed micrometeorological methods to measure dust fluxes and obtain a

regression expression which is similar ( $F = 1.93 \times 10^3 u^{*4.38}$ ,  $F$  in  $\mu\text{g m}^{-2} \text{s}^{-1}$ ). In comparison, *Tegen and Fung* [1994] used an earlier relationship from *Gillette* [1978] which relates the dust flux to the wind speed raised to the third power ( $F = C_{\text{TF}} U^3 (U - U_c)$ ,  $F$  in  $\mu\text{g m}^{-2} \text{s}^{-1}$ ,  $C_{\text{TF}} \sim 1 \mu\text{g s}^2 \text{m}^{-5}$ ).

For application in CP<sup>3</sup>, preliminary threshold friction velocities were determined corresponding to several different land use types, soil types, vegetative residue, and time of year (to account for farming practices). For initial model applications, events were considered during the fall of the year (in September and in November), when the land is most susceptible to wind erosion. The threshold friction velocities given in Table 2 were obtained using results from *Gillette* [1988] and also preliminary results from *Stetter and Saxton* [1995], who used a portable wind tunnel to measure dust emission rates from a variety of cultivated soils in eastern Washington as part of the CP<sup>3</sup> project. For the highly erodible soils from the center of the modeling domain (soil type L<sub>1</sub> and L<sub>2</sub>) during the fall in a fallow year, the threshold friction velocity is estimated as  $0.4 \text{ m s}^{-1}$ . However, for a grid designated as dry agricultural land, only half of the grid is assumed to be fallow at any specific time. The other half is assumed to contain a modest level of vegetative residue and thus has a threshold friction velocity of  $1.2 \text{ m s}^{-1}$  for the same soil type. In contrast, irrigated land in late fall is assumed to be bare, and this applies to the entire grid, since the irrigated land is not rotated on a cultivated/fallow basis. As a result, for a given soil type, irrigated land will yield a higher grid emission rate than dry cropland.

In the EMIT model, the digital maps of land use category and soil type are employed with the flux algorithm to calculate 1 km gridded emissions where the predicted atmospheric friction velocities are taken from CALMET at the 4 km grid scale. In turn, these small-scale emission estimates are summed back to the 4 km scale to provide hourly gridded emissions for input to the CALGRID model. The objectives of this scheme are to maintain the maximum amount of information related to the dust emission process, to determine transport and dispersion at a larger scale, and to minimize required computer resources. It should be recognized that this method assumes that the surface characteristics are homogeneous within each 1 km grid area and that the effects of local topography [at scales less than 4 km] and the scale of local fields are not accounted for explicitly.

#### 4.3. PM<sub>10</sub> Transport, Dispersion, and Deposition Modeling

For the purpose of calculating PM<sub>10</sub> concentrations, CALGRID provides a basis to treat inhomogeneous terrain, varying stability conditions, dry deposition of particles, and spatial and temporal variations of grid scale emissions. In CALGRID, concentrations

of PM<sub>10</sub> are determined from the solution of the K theory form of the atmospheric diffusion equation:

$$\frac{\partial C}{\partial t} + U_i \nabla C = \nabla(K \nabla C) + S + D \quad (2)$$

where  $U_i$  is the vector wind field,  $K$  is the eddy diffusivity tensor,  $S$  represents the source term, and  $D$  represents particle deposition.

To solve the horizontal advection/diffusion portion of the equation, the model uses the Blackman cubic polynomials scheme [Yamartino, 1993]. This scheme exhibits lower numerical diffusion than the original method used in CALGRID. Negative concentrations are prohibited by a filter and a subsequent mass borrowing scheme.

The horizontal diffusivities can be specified by the user and may include the diffusivity associated with induced diffusion due to distortion or stress in the horizontal wind field as developed by *Smagorinsky* [1963]. CALGRID uses a terrain-following vertical coordinate system. The model provides for arbitrary and spatially varying spacing of vertical levels. The vertical diffusivities in CALGRID are calculated based upon convective scaling in the daytime boundary layer and local scaling in the nighttime boundary layer.

Dry deposition rates of gases and particulate matter can be evaluated by a full resistance-based model based upon the work by *Hicks* [1982] and others [Slinn and Slinn, 1980; Pleim et al., 1984]. However, for the initial model runs presented in this paper, deposition velocities were assumed to be constant at  $1 \text{ cm s}^{-1}$ , and deposition flux was calculated in CALGRID as  $F_d = -v_d C$ , where  $C$  is the predicted particle grid concentration in the first layer of the model domain.

#### 4.4. Modeling Domain, GIS Maps, and Meteorological Observations

The modeling domain extends from the eastern base of the Cascade Mountains in Washington to the western side of the Bitterroot Mountains in Idaho and covers the extent of the Columbia Plateau north to south as indicated in the digital terrain map in Figure 1a. To obtain as much detail as possible and still achieve reasonable model run times, the model grid was selected with a 4 km horizontal scale which yields a model grid measuring  $100 \times 85$  grids. Five vertical layers were selected with upper boundaries as follows: 20, 100, 500, 1000, and 2000 m.

A land use (vegetative cover) classification (Plate 1) and a soils map (Plate 2) were created to support the generation of PM<sub>10</sub> emissions for dust event modeling [Vaughan and Frazier, 1995]. The land use classification was developed from 1990 two week composite AVHRR NOAA-11 satellite imagery, with 1 km resolution (1 pixel equals  $1 \text{ km}^2$ ), available on CD-ROM [U.S. Geological Survey, 1993]. The image analysis technique of unsupervised multispectral clustering [Schowengerdt, 1983] was applied to the visible and near-infrared channels of composite images from May through November, under a mask that eliminated major water bodies. The spectral classes from a September 1990 image were then combined to represent five target land use classes (water, forest, range, irrigated agriculture, and dryland agriculture) based on the contributing pixels' association with the domain landscape.

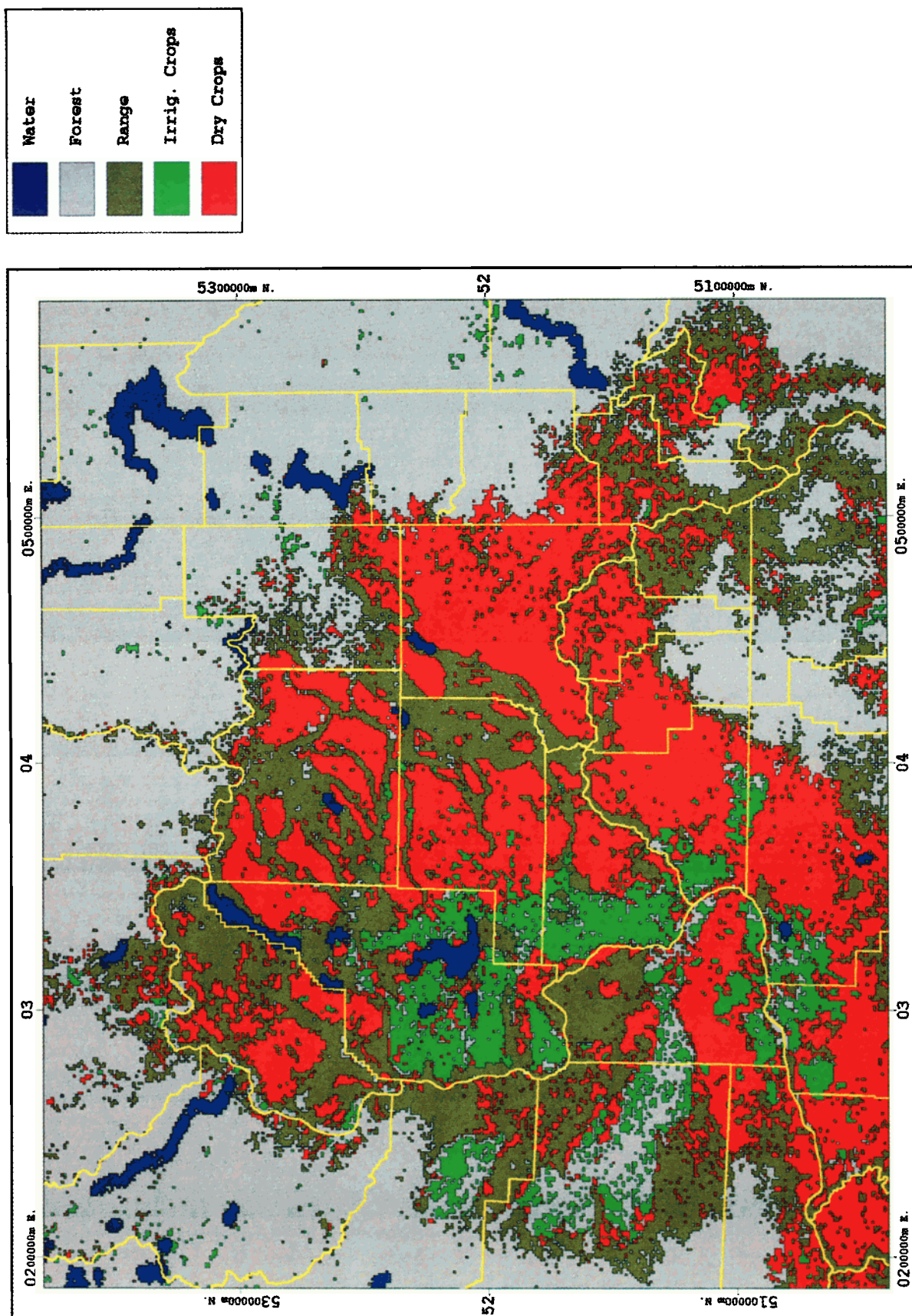
The land use classification was further refined based on ground truth observations, and was then evaluated using a vegetation index [Vaughan and Frazier, 1995]. The first method used

**Table 2.** Summary of Estimated PM<sub>10</sub> Threshold Friction Velocities as a Function of Soil Type and Vegetative Residue

Soil Type	Land Use			Range Land
	Irrigated Bare	Dryland Fallow	Dryland Residue	
L1	0.40	0.40	1.20	1.03
L2	0.54	0.40	1.48	1.32
L3	0.63	0.40	1.56	1.44
L4	0.74	0.74	1.60	1.54
L5	0.80	0.80	1.60	1.60

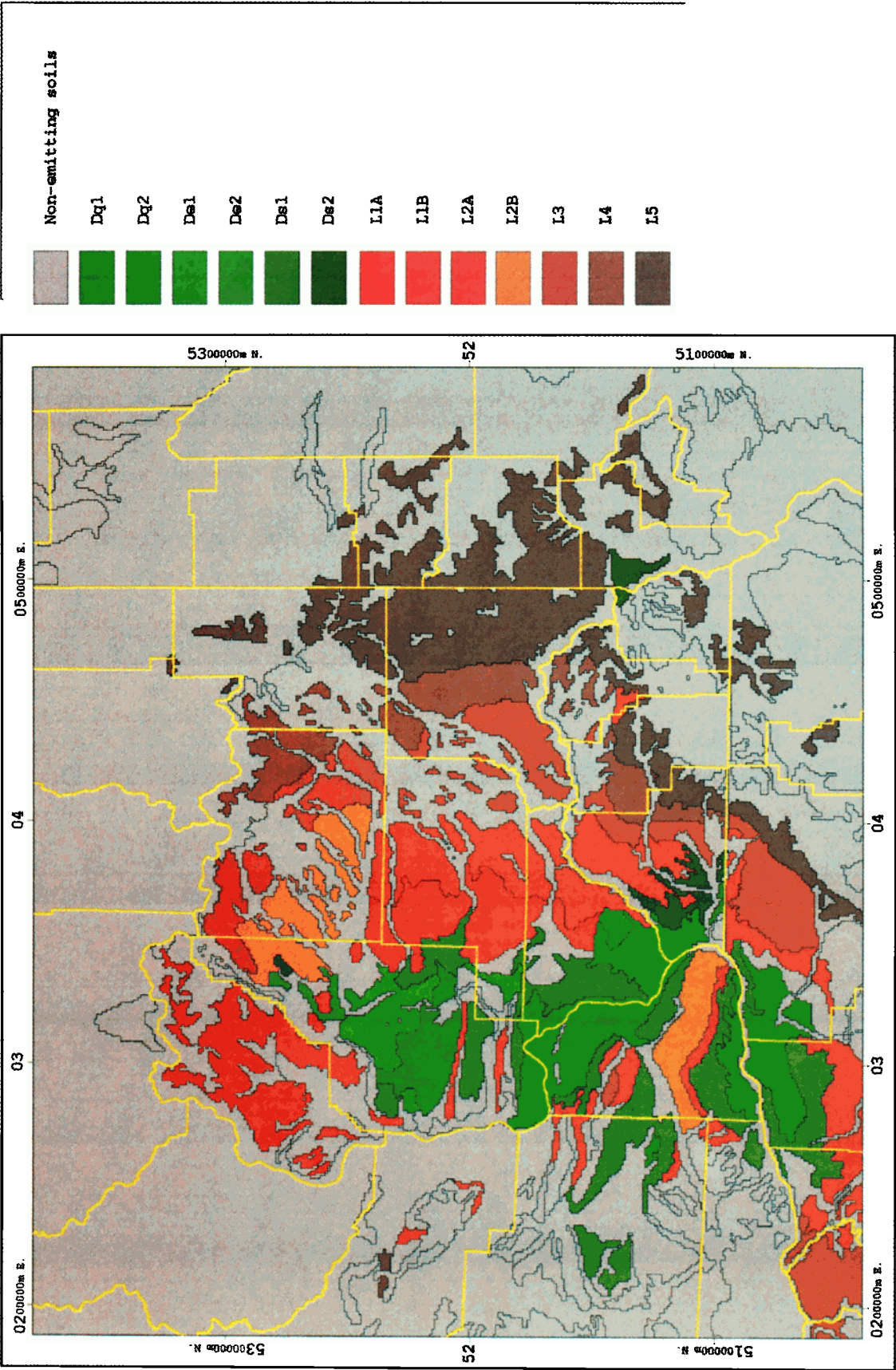
L1, most erodible soil type; L5, least erodible soil type. Data from *Gillette* [1988], and *Stetter and Saxton*, [1995]. Values are in units of  $\text{m s}^{-1}$ .





**Plate 1.** Vegetation classification from AVHRR composite imagery for September 1990, for the CP3 domain.





**Plate 2.** Soils for the CP<sup>3</sup> domain, with emphasis on soils of high wind erosion and PM<sub>10</sub> emission potential. Soil classifications are discussed by *Boling et al.* [1997; *U.S. Department of Agriculture*, 1984, 1986].

ground truth observations collected in summer of 1994 within the CP<sup>3</sup> domain. The second method used the normalized difference vegetative index (NDVI) [Tucker, 1986] from a sequence of eight images spanning April through December of 1990 to test the uniqueness of the September-based land use classes. The NDVI method was a test of whether the spectral behavior of pixels classified together was or was not consistent across time. The NDVI behavior from like classified pixels within each quadrant was appreciably unique relative to the other classes within that same quadrant.

The soils geographic information system (GIS) data layer was constructed from a previously digitized map of Washington General Soils [Boling *et al.* 1997], combined with additional digitized soils data from Idaho and Oregon. The combined soils map was cut to the CP<sup>3</sup> domain for use in the emissions processing code. The "L" series of soils represent the erodible classes of soils in the dryland agricultural areas, while the "D" series of soils represent the erodible classes of soils for the irrigated agricultural areas. For simplicity, it was assumed that other soil types in the domain were not susceptible to wind erosion (e.g. soils occurring in the forested areas). The resulting land use types and soil types were taken from these 1 km scale maps and averaged to the 4 km scale as input to CALMET. The 1 km scale was maintained in these input maps for use in the EMIT model.

Relatively dense meteorological observations are available in the central to southwestern portion of the modeling domain, but available stations are very sparse in the northeastern portion of the grid. The network consists of a surface Public Agricultural Weather System (PAWS) maintained by the WSU Agricultural Extension Office, a surface Regional Automated Weather System (RAWS) maintained by the U.S. Forest Service, surface stations on and around the Hanford Nuclear Reservation, and a very few surface stations operated by the National Weather Service (NWS).

The only upper air site in the domain is the Spokane station, which provides standard twice daily rawinsonde observations. The combined meteorological network is shown in Figure 1b.

The PAWS stations collect 15 min average measurements of wind speed, direction, temperature, dew point, and at some stations, soil moisture and solar radiation. The measurement heights are either 10 m or 2 m for most of the network. The RAWS stations provide similar wind speed, direction, temperature, and dew point data. For modeling purposes, all of the surface meteorological data were averaged to 1 hour for input to CALMET.

## 5. Results and Discussion

The most severe windblown dust events occur during the relatively dry period from early September to mid-November, when the agricultural fields in the Columbia Plateau are most fragile; however, dust storms can also occur in the spring and early summer. Here we describe the baseline conditions and discuss meteorological and particulate measurements collected during two major fall events and one minor summer event. Then the modeling system is demonstrated using results from the two fall events.

### 5.1. Baseline (Nonevent) Data

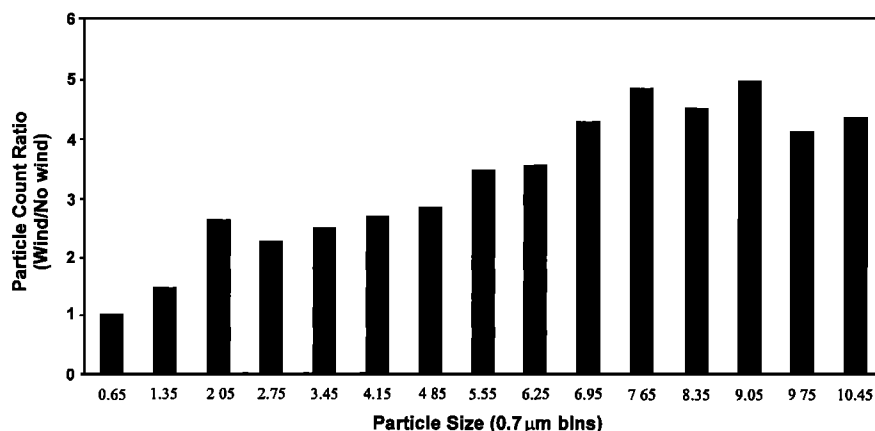
Under relatively calm conditions in the fall, PM<sub>10</sub> levels throughout Adams County tend to be under 50 µg m<sup>-3</sup> and, typically, are 20 to 40 µg m<sup>-3</sup> (Table 3). The results averaged over all of the network sites during the 1993 period (excluding November 3) yielded a background concentration of 28 ± 17 µg m<sup>-3</sup>. A continuous PM<sub>10</sub> analyzer was operated at the TNWR during the fall of 1994 and 1995. In 1994 the overall average background concentration at TNWR was 34 ± 24 µg m<sup>-3</sup> for the period of August 24 to October 10, and 10 ± 10 µg m<sup>-3</sup> for the

**Table 3.** Background Particulate Matter Concentrations Measured by the Adams Co. Network for the Windblown Dust Season of 1993 and 1995

Date	Site								Site Average
	1	2	3	4	5	6	7	8	
September 20, 1993		24	6		24	26			20±9
September 22, 1993		4	38	7	9	44			20±19
September 24, 1993		51	81	32	27	42			47±21
September 29, 1993	60	37			22		38	44	40±14
October 1, 1993	19	30	19	19	27		17	12	20±6
October 3, 1993	27	46	30	32	30		26	34	32±7
October 5, 1993	72	105	39	31	19		37		51±32
October 6, 1993	19	22	7	7	24		29	78	28±23
October 8, 1993						26		9	18±12
October 11, 1993	35	39	42	26	18	27	20	28	29±9
October 13, 1993	38	39	25	29		27	22		30±7
October 16, 1993	24	35	24	23	18	27	30		26±5
October 19, 1993	13	19	12	2	3		8		10±6
October 21, 1993	30	44	37	23	40	30		25	33±8
October 24, 1993	21		21				8	2	13±10
October 27, 1993	32	42	28	14	26	38	32	48	33±10
October 28/93		6	9	15	16	20	12	27	15±7
Average (1993)	32.5	36.2	27.9	20.0	21.6	31.3	23.3	30.7	
July 27, 1995				25.7	16.5	10.7			18±6
August 10, 1995				20.8	21.8	17.4			20±2
August 24, 1995		32.3			31.4		36.1		33±2
Average (1995)		32.3		23.3	23.2	14.1	36.1		

PM<sub>10</sub> concentrations are given in µg m<sup>-3</sup>.





**Figure 3.** Ratio of particle counts by size for windy and nonwindy periods measured from the summit of Steptoe Butte in June 1994.

period of October 10 to November 28. The lower concentrations later in the season, shown in Figure 3, are consistent with an increased probability of rainfall in October and November. For establishing baseline concentrations, no data from 1995 were considered because that season was abnormally wet.

## 5.2. Particle Size Distributions

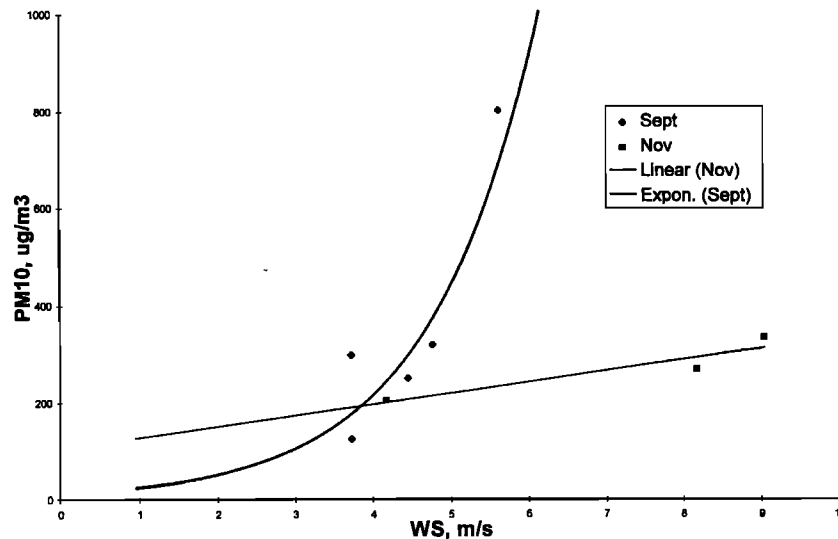
In addition to the  $PM_{10}$  mass concentration measurements made during the 1993–1994 period, a laser aerosol spectrometer (LAS) was periodically used to determine the particle size distributions which occur during windy periods compared to those during nonwindy periods. The particle size characterization has implications for the radiative effects of dust storms as well as effects on human health. Figure 3 shows the enhancement of particle number during windy events compared to nonwindy periods measured from the summit of Steptoe Butte for windy (June 13) versus nonwindy (June 22) days. On June 13, 1994, wind speeds were high at Othello during the day: 7 to 9  $m\ s^{-1}$  between 0700 and 1500. June 22 was a low wind speed day with wind speeds that were below 4.5  $m\ s^{-1}$ . Figure 3 shows that, at Steptoe Butte, there is enhancement by a factor of 5 of number concentrations at size fractions above approximately 5  $\mu m$ , on June 13 compared to June 22. This would be expected, since windblown dust is thought to have a more significant effect on the coarse size fraction compared to the fine size fraction. In addition, slightly higher number concentrations in all size ranges were observed on the windy day compared to the nonwindy day. This is an important observation because it shows that windblown dust may contribute more fine particulate matter than previously thought. Size distribution of mineral dust aerosol measured during dust storms in the Kafirnigan Valley, Tadjikistan [Sviridenkov *et al.*, 1997] also indicated mineral dust contributions to the mass of particles smaller than 2  $\mu m$ , and in fact, showed a large population of particles in the size range of 1 to 10  $\mu m$ . Gillies *et al.* [1996] measured particle size volume distributions in Mali and observed a bimodal distribution with maxima at approximately 5  $\mu m$  and at 44  $\mu m$  which they attributed to a combination of near and far sources. In the present data the volume distribution (not shown) is unimodal, with a peak near 8  $\mu m$ . Gomes *et al.* [1990] measured particle mass distributions during dust storms in Algeria which contained bimodal distributions with maxima at approximately 0.3  $\mu m$  and 3  $\mu m$ . The smaller maxima were not observable in our

measurements due to the lower size limits of the LAS instrument (0.3  $\mu m$ ).

## 5.3. Wind Event Data

Although the primary windblown dust season occurs from September 1 to November 30, there have been no major dust storms in eastern Washington since the complete sampling network has been deployed. Two major dust storms occurred during the fall of 1993 (September 11 and November 3), and limited particulate data were collected, including continuous  $PM_{10}$  in Spokane. Both events have been modeled and are discussed below. A windblown dust event also occurred on July 24–25, 1994. At the NZ site in Spokane the 24 hour  $PM_{10}$  concentration was 109  $\mu g\ m^{-3}$  for July 24. At the CZ site the value was 129  $\mu g\ m^{-3}$ . There was a significant increase in the  $PM_{10}$  levels in Spokane near midnight on July 24. The  $PM_{10}$  concentrations increased from 42 to 176  $\mu g\ m^{-3}$  at the CZ site and from 34 to 120  $\mu g\ m^{-3}$  at the NZ site. There was also a slight increase in  $PM_{2.5}$  concentrations during this time at the CZ site (15 to 22  $\mu g\ m^{-3}$ ) [Haller *et al.*, 1997]; however, the  $PM_{2.5}$  at NZ did not increase. The wind speed measured at the CZ site showed a marked increase just prior to the increase in  $PM_{10}$ . Wind speeds over 10  $m\ s^{-1}$  were not sustained for the duration of the high particulate levels.

Results from events between 1990 and 1993 obtained from the Spokane agency monitoring sites are summarized in Figure 4 in terms of the 24 hour average  $PM_{10}$  concentration measured in Spokane versus the 24 hour average wind speed measured in the central basin. The results indicate the dramatic effects of changes in soil conditions through the fall upon  $PM_{10}$  concentrations at downwind receptors. In September,  $PM_{10}$  concentrations increase exponentially as wind speeds increase above 5  $m\ s^{-1}$ . In contrast, there appears to be a slow linear increase in concentrations in November as wind speeds increase to near 10  $m\ s^{-1}$ . The difference in this behavior is related to the accumulation of precipitation from September to November and to changes in soil cover as fallow fields are seeded and begin to grow during the fall. This pattern is very similar to the results presented by Holcombe *et al.* [1997], who found a correlation between dust episodes along the California–Arizona boundary and cumulative precipitation preceding the episodes. Holcombe *et al.* attributed changes in threshold velocity to increased vegetation growth due to increased precipitation.



**Figure 4.** Relationship of measured 24 hour average  $PM_{10}$  concentrations in Spokane, with 24 hour average wind speed measured in the central basin of Washington for early and late fall time periods.

#### 5.4. Initial Model Applications

Initial  $PM_{10}$  concentrations were taken to equal typical background (nonevent) concentrations obtained from the monitoring program. For events prior to October 15, the background concentration was assumed to equal  $34 \mu\text{g m}^{-3}$ , and for events after October 15, the background concentration was assumed to equal  $10 \mu\text{g m}^{-3}$ . Since the forested Cascade Mountains and the Pacific Ocean lie upwind of the modeling domain, boundary conditions were assumed to equal these same nonevent background concentrations throughout the duration of each event.

Very limited ambient measurements of  $PM_{10}$  are available for evaluation of the regional windblown dust modeling system. In addition, work is continuing to refine the emission algorithm from systematic field and portable wind tunnel measurements in the CP<sup>3</sup> domain. For that reason, the model was applied to several recent dust events, the observations at the available monitoring sites were used to calibrate the dust constant (1), and the model was rerun with the empirical dust constant. As will be shown, the changes in the dust constant based upon this calibration are consistent with existing soil moisture histories for these events. Thus the initial model applications are useful for defining the emission algorithm as well as for providing a detailed description of the nature of these northwestern dust storms.

#### 5.5. September 11, 1993

On September 11, the southwesterly winds generated by the counterclockwise circulation of a low-pressure system centered approximately over Calgary, Alberta, were enhanced by the clockwise circulation around a high-pressure system south in mid-Nevada (Figure 2). The hourly averaged wind speeds measured in the Columbia Plateau, for September 11, 1993, increased from  $2 \text{ m s}^{-1}$  early in the morning to a peak wind speed near  $10 \text{ m s}^{-1}$  at 1800 and then decreased back to  $3 \text{ m s}^{-1}$  by early evening (Figure 5). During the windy period, the wind direction at the Columbia Basin sites was from the SW to WSW.

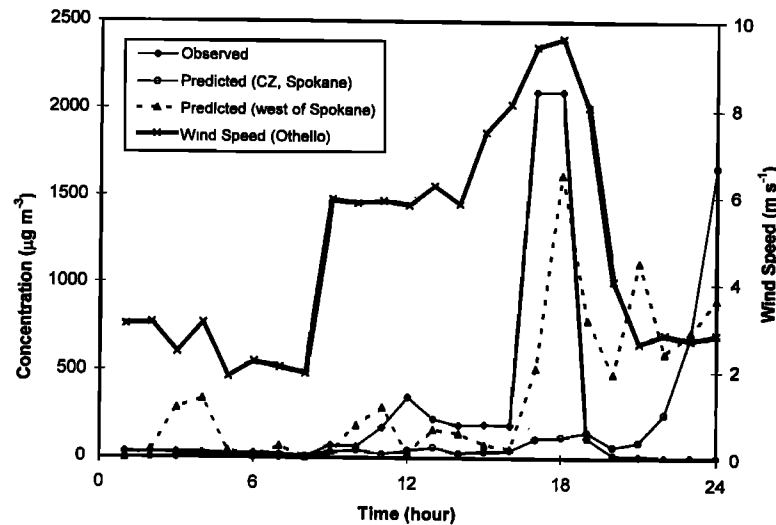
This event produced 24 hour averaged  $PM_{10}$  concentrations greater than  $200 \mu\text{g m}^{-3}$  in Spokane and greater than  $100 \mu\text{g m}^{-3}$  in Kennewick. Continuous  $PM_{10}$  measurements were also collected on this day at the CZ and NZ sites. From the CZ monitor, two

concentration peaks were observed; one appeared at 1200, when the concentration exceeded  $300 \mu\text{g m}^{-3}$ , and the second appeared at 1700, when the concentration exceeded  $2000 \mu\text{g m}^{-3}$  (Figure 5). This concentration is similar in range to mass concentrations ( $1000$  to  $9000 \mu\text{g m}^{-3}$ ) of particles smaller than  $20 \mu\text{m}$  measured in the source region during windblown duststorms in Tadzhikistan [Gillette *et al.*, 1993].

For this event the peak wind speeds were predicted to occur in the center of the domain, and thus predicted emissions were also at a maximum in the center of the domain. Emissions began to occur as early as 1000, but a rapid increase in emissions began at approximately 1400, with peak emissions occurring at 1700. Total domain emissions during the 24 hour modeling period equaled 64 Gg from dryland agriculture soils, 39 Gg from irrigated agriculture soils, and 13 Gg from rangeland soils. The total deposition within the domain during the 24 hour simulation period equaled 39 Gg. Surprisingly, the total emission estimate for this single storm is equal to approximately 1% of the global annual rate ( $3000 \text{ Mt yr}^{-1}$ ,  $8200 \text{ Gg d}^{-1}$ ) estimated by Tegen and Fung [1994, 1995]. The significance of a single storm with respect to the global estimate is a clear indication of the importance of extreme events in dust production. It is important to note that the global estimates are based upon model calculations using a 6-hour temporal resolution and  $1^\circ \times 1^\circ$  spatial resolution, while our estimates are based upon hourly timescales and  $1 \text{ km} \times 1 \text{ km}$  resolution. At the same time, the fact that deposition represents approximately 40% of the emissions during the simulation period indicates that the impact upon the atmosphere is short-lived in terms of the mass loading of dust.

The predicted 24 hour averaged  $PM_{10}$  concentrations for the domain are shown in Figure 6. Extremely high concentrations are predicted in the source region in the vicinity of Kennewick, and a large, complex plume stretches from the center of the Plateau toward the northeast. It appears that the predicted plume bypasses Spokane to the north with only a fringe of the plume impacting the urban area. Vertical cross sections of the predicted concentrations show that this large plume of dust diffuses to less than 400 m above the surface during transport.

In Figure 5, the predicted time series for Spokane is shown along with the predicted time series for a grid approximately 35 km west of Spokane. The predicted  $PM_{10}$  concentrations in



**Figure 5.** Hourly wind speed measured in the Columbia Plateau, and observed and predicted hourly  $PM_{10}$  concentrations in Spokane, for the windblown dust event of September 11, 1993. Predicted concentrations for a grid immediately west of Spokane are also shown.

Spokane do not show the large observed maximum in concentrations around 1700, but rather indicate steeply increasing concentrations near midnight. However, at the grid located just to the west of Spokane, the predicted time series indicates maximum concentrations at the same time as those observed. These predicted patterns, in comparison to the observations, suggest that the plume transport direction predicted with the modeling system is not correct. This is probably related to the sparseness of the available meteorological data in the northeastern quadrant of the domain.

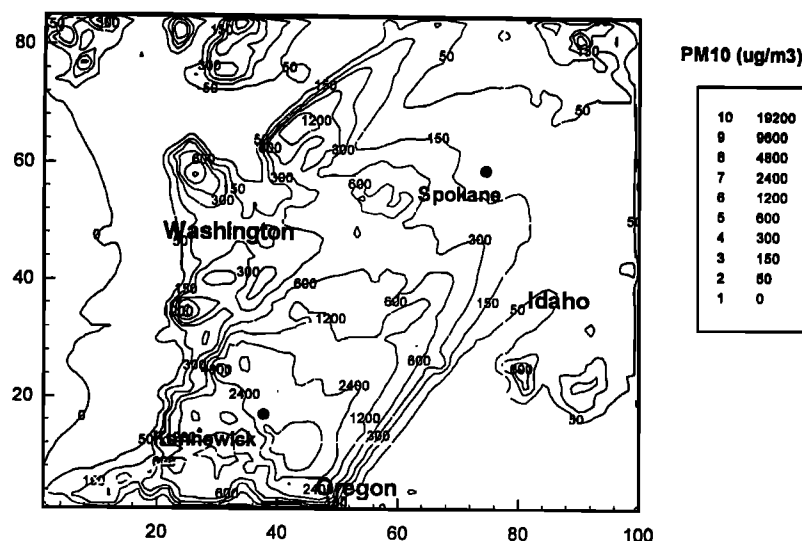
The results for this case were achieved by adjusting the empirical dust emission constant  $C$  to equal  $9.6 \times 10^{-3} \text{ g s}^3 \text{ m}^6$  based upon the 24 hour average  $PM_{10}$  concentrations observed in Spokane and in Kennewick.

### 5.6. November 2 and 3, 1993

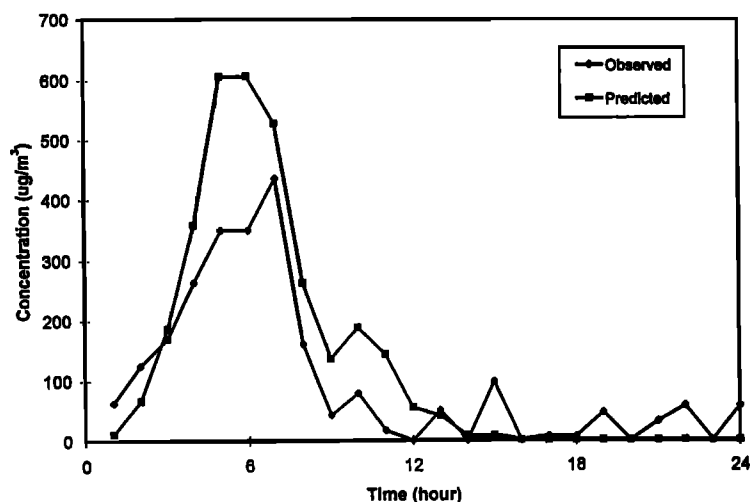
A major dust storm also occurred later in the season of 1993. Wind speeds above  $7 \text{ m s}^{-1}$  were observed in the Columbia Plateau from 2100 to 2300 the night before, and then from

approximately 0200 until mid-day. In the early morning the wind was from the SSW until about 0400, and then it shifted to westerly for the remainder of the day. Concentrations in Adams County ranged from 12 to  $187 \mu\text{g m}^{-3}$  (the network was not deployed in time to capture the entire event). In Spokane the  $PM_{10}$  maximum hourly observed concentration at NZ occurred in the very early hours (around 0200 to 0800), with the highest hourly average equal to  $440 \mu\text{g m}^{-3}$  at 0700. After approximately 0700, the  $PM_{10}$  levels abruptly decreased.

On November 3 the maximum predicted emissions occurred at 0500 at the same time as the maximum predicted wind speed of  $26 \text{ m s}^{-1}$ . The maximum winds and emissions were predicted to occur near the center of the domain in the Horse Heaven Hills west of Kennewick. The domain total emissions during November 3 were 51 Gg for dryland agriculture, 27 Gg for irrigated agriculture, and 2.9 Gg for rangeland. Total deposition during the simulation within the domain was estimated to equal 45 Gg. These emission and deposition values are similar to those from the September dust storm.



**Figure 6.** Predicted surface layer  $PM_{10}$  concentrations averaged over 24 hours for September 3, 1993.



**Figure 7.** Observed and predicted hourly  $PM_{10}$  concentrations in Spokane for the November 3, 1993, dust event.

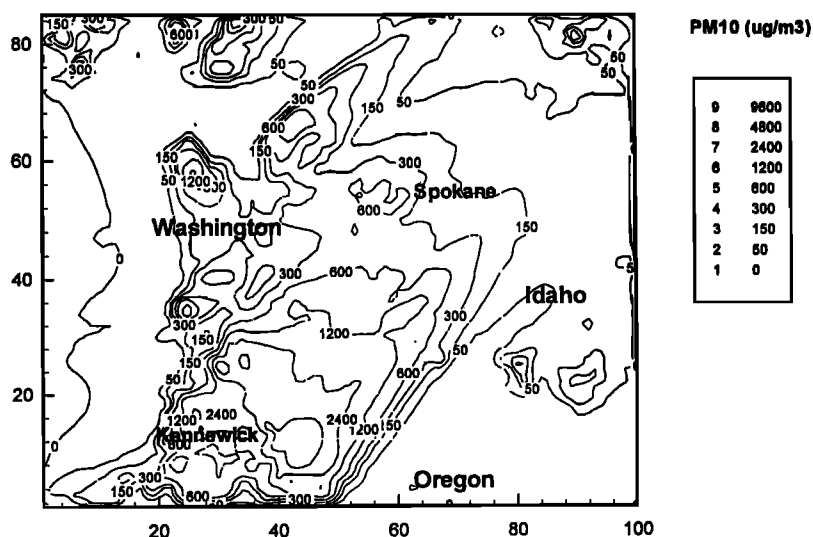
During November 2, the predicted time series of  $PM_{10}$  at NZ exhibited essentially background levels during the day and began increasing above  $50 \mu g m^{-3}$  near midnight. The predicted hourly concentrations reached a maximum from 0500 to 0600 on November 3, slightly earlier than observed, as shown in Figure 7. The measured maximum hourly concentration equaled  $440 \mu g m^{-3}$ , while the predicted maximum hourly concentration reached  $600 \mu g m^{-3}$ . The fact that the timing of the maximum is in good agreement between observations and predictions suggests that, in this event, the model correctly predicted the winds and transport. The 24 hour averaged dust plumes predicted with the model indicate highest impact in the center of the domain and in the region upwind of Spokane, as shown in Figure 8. The dust constant was adjusted to equal  $1.5 \times 10^{-3} g s^{-1} m^{-6}$  based upon observed concentrations in Spokane and Kennewick.

### 5.7. Model Calibration and Evaluation

For these initial modeled events, the agreement between the model and measurements, after calibration of the dust constant, is within approximately 20% at the Spokane urban sites (Table 4).

At the same time, however, the model significantly underpredicted 24 hour average concentrations in Kennewick in both cases, but overestimated concentrations at the rural TNWR site during the first event. There is a relatively large amount of housing development under way in the Kennewick area. Dust from these construction sites may dominate local observations. At the rural TNWR site, there is no similar explanation as to why the model overestimated the observed concentrations. Further work is needed to explain observations at TNWR. During the first case, the model did not predict the timing of the maximum in Spokane, although it appears that high concentrations were predicted just west of the city at the same time that high levels were observed in the city. In the second case the timing of the maximum was correct in Spokane, and the magnitude of the maximum predicted concentration was approximately 36% higher than the observed maximum concentration.

These events provide a dramatic illustration of the effects of soil conditions upon the potential for windblown dust. As shown in Table 5, the average  $PM_{10}$  concentrations in Spokane and the average surface wind speeds were approximately the same for



**Figure 8.** Predicted surface layer  $PM_{10}$  concentrations averaged over 24 hours for November 3, 1993.



**Table 4:** Observed and Predicted 24 Hour Average PM<sub>10</sub> Concentrations During Two Historical Dust Events

Location	Observed	Predicted	Ratio
<i>September. 11, 1993; C = 9.6 × 10<sup>-3</sup></i>			
NZ, Spokane	255	228	0.9
CZ, Spokane	300	248	0.8
SA, Spokane	297	281	1.0
Kennewick	118	424	3.6
Turnbull Refuge	490	261	0.5
<i>November. 3, 1993; C = 1.5 × 10<sup>-3</sup></i>			
NZ, Spokane	100	96	1.0
CZ, Spokane	207	180	0.9
SA, Spokane	156	147	0.9
MW, Spokane	176	178	1.0
Kennewick	1166	1899	1.6

Observed concentrations in Spokane and Kennewick were used to calibrate the dust emission model through adjustment of the dust constant  $C$  ( $\text{g s}^3 \text{m}^{-6}$ ). PM<sub>10</sub> concentrations are in  $\mu\text{g m}^{-3}$ .

these two events, but the value of the dust constant was decreased by a factor of 6 between the two events. During September, harvest in the irrigated areas was mostly complete, and seeding in the dryland areas was also mostly complete, so that the newly seeded lands were covered with the powdery dust mulch. There was essentially no precipitation in the region during the preceding month. As a result, the region was in an extremely susceptible state, so that a moderately strong wind could produce an intense dust storm. In contrast, the November event occurred long after seeding was complete, and there was some winter wheat above ground in fields that had been planted. The cumulative precipitation equaled 3.5 mm. The differences in the dust constant for these two events are thus quite consistent with changes in soil conditions between an early fall period when the soils are most fragile and a late fall period where some precipitation had occurred and more vegetation existed. Further work is required to incorporate parameters such as cumulative precipitation or soil moisture into the emission model in a quantitative manner.

*Gillette and Passi* [1988] estimated values of the dust constant at approximately  $10^{-3}$  for midwestern U.S. soils using aircraft dust measurements. This is very similar to the dust constant for the November dust, but it is a factor of 10 less than the dust constant for the September storm. This may suggest a change in soil aggregate size distribution from a very fine powdery soil in September to a more sand-like soil aggregate in November, similar to sandy midwestern soils, as a result of autumn accumulation of precipitation.

*Armbrust and Bilbro* [1997] investigated the effects of plant cover upon soil transport and showed that the threshold wind

speed increases with the plant area index. In our initial applications and calibration of the emission model, we accounted for this effect to a first order by assigning different threshold velocities to different soil and landcover types. Effects of soil moisture, changes in field roughness, and changes in vegetative residue are all incorporated through adjustment of the dust constant. Given the limited amount of observations and the complex mix of soil types and landcover, it was not possible to make further adjustments to the threshold velocities to account for these effects. Furthermore, in the current development of a more complete dust emission algorithm for the CP<sup>3</sup> region, these other effects are being treated through incorporation of erodibility, field roughness, vegetative cover, and soil moisture factors within the algorithm. Threshold velocities are taken as constants by soil type and as indicators of the fundamental tendency for the soil to erode.

The flux algorithm with the calibrated dust constants for the two events can be compared to the algorithms reported by *Nickling and Gillies* [1993] and that derived by *Tegen and Fung* [1995], who calibrated their dust constant by comparing predicted global optical depths, concentrations, and deposition rates to observed values. In Figure 9, predicted dust flux versus friction velocity is shown for a case with the threshold friction velocity equal to  $0.4 \text{ m s}^{-1}$ , corresponding to a highly erodible soil in our domain. There is a significant difference in the estimated fluxes between the September and November events, but the range of these CP<sup>3</sup> curves encompass the regression curve from *Nickling and Gillies* [1993] for West African soils and also the curve employed by *Tegen and Fung* [1995] to represent undisturbed soils. For disturbed soils, Tegen and Fung estimated dust constants in the range from 43 to  $179 \mu\text{g s}^2 \text{m}^{-5}$ . However, even the lower end of this range yields a radically higher flux (in Figure 9), which appears to be excessively large compared to the flux for September 93, where soils in the CP<sup>3</sup> domain were in a very fragile state. As indicated previously, our estimates are based upon hourly averaged winds with a correction to account for short-term gusts, while the estimates from Tegen and Fung are based upon a 6 hour time step and a much larger spatial grid size.

## 6. Summary and Conclusions

The Columbia Plateau PM<sub>10</sub> Program is an extensive, ongoing effort to understand the nature of windblown dust on a regional scale in an area of intensive agriculture. Given global demands to increase agricultural operations, understanding the contribution of regional agriculture to global mineral aerosol burdens is an important aspect of Earth's radiation budget and climate change. In the initial stages of the CP<sup>3</sup> program, ambient background concentrations in this rural area ranged from  $34 \mu\text{g m}^{-3}$  during the

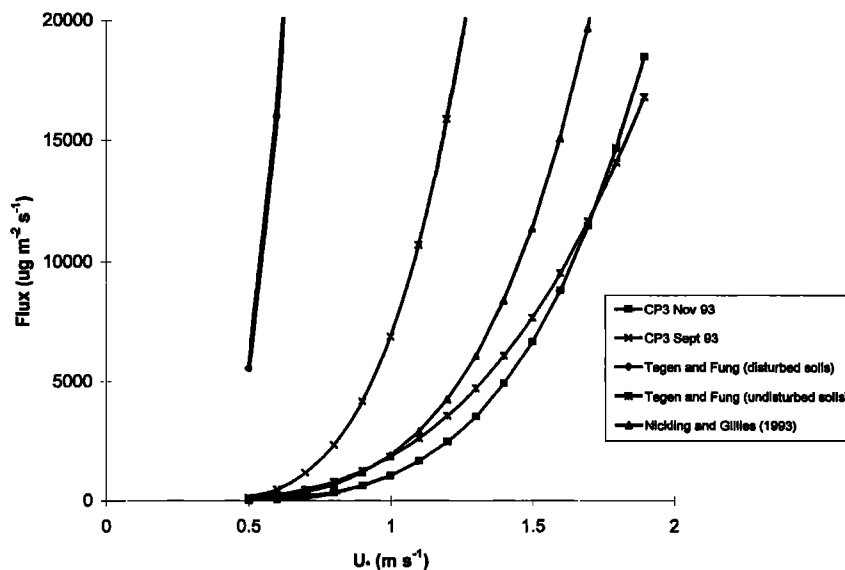
**Table 5.** Summary of Mean Parameters During Dust Storms in Early and Late Fall

Date in 1993	Mean PM <sub>10</sub> Spokane, $\mu\text{g m}^{-3}$	Mean Wind Speed, <sup>a</sup> $\text{m s}^{-1}$	Wind Energy, <sup>b</sup> $\text{m}^3 \text{s}^{-3}$	1-Month Cumulative Precipitation from Sept. 1, 1993, <sup>c</sup> mm	Calibrated Dust Constant $C$ , $10^{-3} \text{g s}^3 \text{m}^{-6}$
Sept. 11	228	4.9	1754	0.01	9.6
Nov. 3	213	5.6	2099	3.5	1.5

<sup>a</sup>Wind speeds are 24 hour averages at 3 m near the center of the domain.

<sup>b</sup>Accumulated 24 hour wind energy based upon hourly wind speeds at 3 m near the center of the domain [Armbrust and Bilbro, 1997].

<sup>c</sup>Cumulative precipitation measured near the center of the domain.



**Figure 9.** Comparison of dust flux algorithms based upon the calibrated dust constants for the September and November 1993 CP<sup>3</sup> storms, calibrated dust constants from *Tegen and Fung* [1995] for disturbed and undisturbed soils, and regression of measured fluxes in West Africa by *Nickling and Gillies* [1993].

dry, early fall to  $10 \mu\text{g m}^{-3}$  during later and somewhat wetter fall months. During this period, the synoptic occurrence of a western Canadian low-pressure system north of the CP<sup>3</sup> region, coupled with a Great Basin high-pressure system south of the area, provides the conditions needed to produce intense winds across the area and to generate large-scale soil transport. These conditions existed during six of seven dust events examined. Maximum ambient concentrations of  $\text{PM}_{10}$  during these dust events can exceed  $500 \mu\text{g m}^{-3}$  on an hourly basis and can average above  $200 \mu\text{g m}^{-3}$  over 24 hours at downwind urban receptors. During windy conditions there is a distinct increase by as much as a factor of 5 in particle counts for sizes above  $1 \mu\text{m}$ .

The development and application of a regional windblown dust air quality model for two fall dust storms shows very heterogeneous distribution of dust emissions across the domain. The dust plume from these sources is predicted to remain within 400 m above the surface during transport. Although detailed ambient data are sparse during these events, the time period for maximum observed hourly concentrations was correctly predicted by the model, and it appears that predicted maximum concentrations are within approximately a factor of 2 of observed maximum concentrations. At urban Spokane sites the predicted concentrations agree to within approximately 20% of the observed concentrations after the model is calibrated via adjustment of the empirical dust constant. However, the model significantly overestimated concentrations at one rural site and underestimated concentrations at a south central urban site. The influence of very local sources or potential problems with local wind stations may be associated with this underestimation.

Changes in the empirical dust constant among the events appear to be consistent with the general state of the soil and the cumulative precipitation in the months preceding each event. This suggests that further work improving the emission algorithm to incorporate the effects of soil history and, particularly, soil moisture will lead to improvements in the overall regional windblown dust model. The values of the dust constant yield flux estimates for the two events which are similar to those from a study in West Africa and to that used by Tegen and Fung to represent undisturbed soils. However, the flux estimates

employed by these authors for disturbed soils appear radically higher than the fluxes estimates for the CP<sup>3</sup> domain.

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