Assessment of the Principal Causes of Dust-Resultant Haze at IMPROVE Sites in the Western United States

Final report

Prepared for:

Western Regional Air Partnership

Prepared by:

Ilias G. Kavouras, Vicken Etyemezian. Jin Xu, Dave DuBois, Mark Green,

Division of Atmospheric Sciences, Desert Research Institute, 755 E. Flamingo Rd. Las Vegas, NV 89119

and

Marc Pitchford

National Oceanic and Atmospheric Administration, Desert Research Institute 755 E. Flamingo Rd. Las Vegas, NV 89119

01/31/2006

1. Introduction

1.1 Background

Dust is the principal component of haze on the 20% worst visibility days of the year ("worst days" hereafter) most frequently at Class I areas in the Western United States. The magnitude of the impact of dust on haze varies by region as well as by season due to source variations in spatial scale, time, location, and causes of emission. For example, paved and unpaved road dust emissions tend to follow the diurnal patterns associated with motor vehicle traffic, with some additional dependence on seasonal occurrences such as snow and agricultural activities. Windblown dust emissions generally occur over larger spatial scales and the magnitude of dust emissions during these events can eclipse the comparatively smaller, but more regular road dust emissions. On a transcontinental scale, enormous, regional dust storms can be transported across oceans and continents and impact the entire WRAP region.

Dust is defined as the sum of Fine Soil mass (FS) and Coarse Mass (CM) as measured by monitors in the IMPROVE network, which operates 24-hr filter samples on a one in three day basis. CM is the difference between PM_{10} and $PM_{2.5}$ fractions. FS is calculated from a linear equation based on the measured concentrations of five metals associated with mineral dust (Al, Si, Ca, Fe, and Ti). The aerosol visibility extinction resulting from suspended aerosols (i.e. does not include Rayleigh scattering) is quantified through the extinction coefficient, $\beta_{ext,aer}$, which is calculated from the equation:

$$\beta_{ext,aer} = 3 \cdot f(RH) \cdot [SO_4^{2-}] + 3 \cdot f(RH) \cdot [NO_3^-] + 4 \cdot [OMC] + 10 \cdot [LAC] + 1 \cdot [FS] + 0.6 \cdot [CM] \qquad \text{Eq. 1-1}$$

where the brackets indicate concentrations of sulfate (SO_4^{2-}), nitrate (NO_3^-), organic carbon (OMC), light absorbing carbon (LAC), fine soil (FS) and coarse mass (CM) in $\mu g/m^3$, respectively and they are inherently subject to both positive and negative sampling and analysis biases. For example, CM originating from sea spray, non-soil organic debris, or from wildfires would result in an overestimate of ambient airborne dust extinction caused by non-dust components.

2. Objectives and methodology

The principal aim of the study was to specifically identify the primary causes of dust measured in the WRAP region by:

1. developing a methodology for assigning worst days when dust constituted the largest contributor to aerosol visibility extinction (worst dust days, hereafter) at IMPROVE monitors within the WRAP domain to a set of source classes;
2. using the methodology to categorize worst dust days over the period 2001 – 2003.

The methodology employs several existing tools in novel ways including air mass backward trajectories, land use maps, and soil characteristics maps. In addition, two new methods have been developed as part of this work. The first is a metric for estimating the contribution of Asian dust to IMPROVE-measured dust on worst dust days. The second utilizes multivariate linear regression of measured dust concentrations vs. nominally local surface meteorological data. These tools were combined using a semi-quantitative approach to preliminarily determine the likely source of dust on a worst dust day at a given site. Due to limitation of the information and capabilities of the tools, the causes of some worst dust days were not determined with any confidence. Using 2001-2003 data from IMRPOVE (and some protocol) monitors in the WRAP regions, each worst dust day was associated with one of these events:

- Transcontinental transport of large scale events from Asia
- Windblown dust events
- Transport of windblown dust from sources upwind (i.e. not from immediate vicinity of site)
    - Further specification if windblown and upwind transport events appears to be regional in nature based on scale of meteorological phenomenon causing dust and number of sites affected
- Undetermined Events

This study focused on 71 sites from the IMPROVE network (and protocol sites) located in the WRAP domain. These sites were selected based on availability of data over the 2001 – 2003 period and the availability of a nearby surface meteorological station over the same period. Table 1 shows the 71 IMPROVE sites considered in this study, the surface meteorological sites used to represent conditions at each IMPROVE site, and distances and elevation differences between the two.

3. Elemental concentrations and ratios: The Asian Dust Score

The transport of airborne dust emitted from high wind events originating in China to the west coast of the US (about 7 – 10 days en route) has received considerable attention in recent years (Cheng et al., 2005; Park et al., 2005; Zhang et al., 2005; Darmenova et al., 2005). Large "Asian dust" events can contribute significantly to haze over large portions of the western US. These large Asian dust episodes are initiated by low pressure systems in the Gobi desert region of Mongolia and northwest China. Once elevated to the troposphere, Asian dust can move fast under zonal flow due to the jet stream. Under high pressure ridge conditions, large-scale exchange of dust from the troposphere to the boundary layer may occur resulting in elevated ground-level mineral aerosol concentrations.

Although it is difficult to quantitatively separate the influence of the Asian dust from dust that is generated on the North American continent or transported from other regions of the world (e.g. Africa), some chemical markers can help identify dust of Asian origin. Perry et al. [1997] and VanCuren and Cahill [2002] suggested that Al/Ca and K/Fe ratios are useful for identifying Asian and African dust. African dust is associated with Al/Ca ratios greater than 3.8, while those ratios for Asian dust are generally less than 2.6. The K/Fe ratio is consistently above 0.5 for Asian dust, while African dust exhibits lower values for this ratio.
Similar chemical markers have been adopted to help distinguish Asian dust from dust generated on the North American continent for this study. The large Asian dust storm on April 19, 1998 was used as a benchmark for establishing these markers. The dust plume from the 4/19/1998 storm crossed the Pacific Ocean, and subsided to the surface of the western United States around 4/29/1998.

For 17 of the WRAP IMPROVE monitoring sites, 4/29/1998 was a worst visibility day with mineral aerosol being responsible for the majority of the reconstructed extinction. Ratios of Al/Si, K/Fe, Al/Ca and CM/Dust (where Dust is the sum of fine soil, [FS], and coarse mass, [CM]), were quite different compared to average values (Table 2). Based on the chemical signature of the 4/19/1998 dust event, ratios of Al/Si, K/Fe, CM/Soil and Al/Ca were used to calculate an Asian Dust Score (ADS):

$$\mathrm{ADS} = \frac{1}{\prod\left(Z_{\mathrm{score(X/Y)}} \cdot \left(\frac{\varepsilon\left(\mathrm{X}/\mathrm{Y}\right)_j}{\left(X/Y\right)_j} \cdot 100 \right)\right)} \qquad \text{Eq. 3-1}$$

where

$$Z_{score(X/Y)} = \frac{\left(\left(X/Y\right)_j - \left(X/Y\right)_{ref}\right)}{\sqrt{\left(\varepsilon\left(X/Y\right)_j^2 + \sigma\left(X/Y\right)_{ref}^2\right)}} \qquad \text{Eq. 3-2}$$

and

$$\varepsilon\left(X/Y\right)_j = \sqrt{\left(\frac{\varepsilon_X}{100}\right)^2 + \left(\frac{\varepsilon_Y}{100}\right)^2} \qquad \text{Eq. 3-3}$$

where $(X/Y)_j$ is the ratio of component X to component Y at a specific site-day j, $(X/Y)_{ref}$ is the reference ratio calculated from the 4/19/1998 dust event, $\sigma(X/Y)_{ref}$ is the standard deviation of the reference ratio, and $\varepsilon(X/Y)$ is the uncertainty of the $(X/Y)_j$ ratio, which is estimated by propagating the measurement uncertainties associated with the X and Y components.

For valid measurements of Al, Si, K, Fe and CM, ADS values are greater than zero, increase when ratios on sampling day j are closer to the reference ratios, and decrease with increasing measurement uncertainty. Thus the ADS does not provide a measure of how much of the IMPROVE sample collected for day j is comprised of Asian dust. Rather the ADS provides a measure of the confidence that measured ratios are close to the Asian dust ratios. With the caveat that even a high ADS value only provides a loose metric for assessing possible Asian dust influence that requires independent verification, based on experience gained in working with ADS ratios, the following approximate guidelines for interpreting the ADS are presented:

- ADS < 750 - small Asian dust signature; Asian influence not likely

- 750 < ADS < 1500, - moderate Asian dust signature; Asian influence should be considered
- ADS > 1500, - strong Asian dust signature; Asian influence is supported by chemical analysis but independent verification or corroborating additional evidence is required for greater confidence

4. Multivariate Linear Regression Analysis (MLRA): Local wind vs. measured dust

MLRA was applied to estimate the impact of local windblown dust by regressing measured dust concentrations against wind direction and speed. 1-hour wind direction (WD) and speed (WS) and precipitation (if available) data were obtained from meteorological sites located at or nearby each IMPROVE site represented in this analysis (See Table 1). In order to reduce the number of permutations of wind speed and direction and to utilize wind direction information in the regression, these met data were transformed into categorical bins (true=1, false=0) (Table 3, Table 4, and Table 5). Since dust mass concentrations were measured on 24-h integrated samples, for each day, the daily sum for each category was calculated. The database was screened using precipitation data when available. In general: (a) A day was removed from the MLRA if precipitation occurred during the sample day for more than 10 hours or on the day prior to the sample day or; (b) Only the last twelve hours (from 12:00 pm to 12:00 am) of a day was removed if precipitation occurred after 12:00 pm.

The concept of multivariate linear regression analysis presumes the ability to predict the value of a dependent variable (y_m) based on the values of n- independent variables (x_i, $i=1,\ldots,n$). The results from MLRA can provide information on the existence of a correlation between dependent and independent variables, an estimate of the accuracy of predicting the dependent variable by using a linear combination of the independent variables, and an estimate of the variation in the dependent variable that can be explained by variations in the independent variables. The equation that describes the multivariate linear regression between measured dust mass on a given sample day at a given site and wind speed and direction characteristics on that sample day is:

$$y_m = y_p + \varepsilon = b_1 \cdot x_1 + b_2 \cdot x_2 + ... + b_k \cdot x_k + a + \varepsilon \quad \text{(Eq. 4-1)}$$

where:

y_m is the measured dust mass concentration;

y_p is the dust concentration estimated by a linear combination of independent variables that describe the wind conditions;

$b_1, b_2, ..., b_k$ are the regression coefficients of the independent variables;

$x_1, x_2, ..., x_k$ are the values of independent variables that describe the wind conditions;

a is the intercept which corresponds to y_p when $x_1, x_2, ..., x_k$ are equal to 0 and;

ε is the residual error - the difference between the y_m and y_p

x_1 , x_2 , …x_k in this analysis correspond to the daily sum of the number of occurrences of 1-hour averaged wind conditions in specific wind speed/direction bins as outlined in Tables 3, 4, and 5. In order to minimize the number of independent variables used in the MLRA, wind conditions corresponding to hourly average speeds less than 14 mph (corresponding to G_1, G_5, G_9, and G_{13} in Table 5) were not included in the analysis. Omission of these low wind speeds was justified on the basis that windblown dust emissions require moderate to high wind speeds. This omission reduces the number of dependent variables from 16 to 12 and greatly reduces the noise in the regressions. The coefficients b_1, b_2,….b_k and a were obtained using the Least-Squares method for the best fit to the data. For each site, the MLRA was run twice, once using the wind direction bins corresponding to column A in Table 4 and once using the bins corresponding to column B.

In order to ascertain the importance of individual independent variables to the overall regression results, variable screening methods (VSM), including stepwise (both forward and backward) procedures, were employed to objectively determine which variables were significant using 0.15 significance level *t*-value criteria. Therefore, the local windblown dust for day *j*, LWD_j, was calculated as follows

$$LWD_j = b_1 G_{1,j} + b_2 G_{2,j} + ... + b_k G_{k,j} \quad \text{Eq. 4-2}$$

where b_1, b_2, ….b_k are equal to the regression coefficients of $G_{1,j}$, $G_{2,j}$, ,,,,,, $G_{k,j}$ when the variable is significant for a specific site and zero when the variable is not significant. The error associated with the estimated LWD_j was provided by:

$$E_j = e_1 G_{1,j} + e_2 G_{2,j} + ... + e_k G_{k,j} \quad \text{Eq. 4-3}$$

where e_1, e_2, ….e_k are the standard errors of the regression coefficients when the variable is significant for a specific site and zero when the variable is not significant. Note that the intercept α was not included in Eq. 3-2 since it represents a “background” dust concentration and not windblown dust derived from the vicinity of the site.

LWD was calculated for all site-days when meteorological data were available. However, LWD values associated with high levels of uncertainty (i.e. $LWD_j - 2 \cdot E_j \leq 0$) were replaced with zero, signifying low confidence in any dust mass concentrations on day *j* estimated from wind conditions. This resulted in meaningful MLRA results for 42 of the 71 sites considered in the analysis. Polar diagrams of standardized regression coefficients and scatter plots of estimated LWD vs. total measured dust for all IMPROVE sample days (including non-worst dust days) for those 42 sites are presented in Figures 1 through 42 (See below for an explanation of polar and scatter plots). Note that the choice of wind direction bins (A vs. B in Table 3) affects the quality of the regression results – though for most of the sites, the difference between choosing A or B is quite small. Whichever choice provided the better fit was used to calculate final values of LWD for a given site and the polar and scatter plots in Figures 1 – 42 represent that choice.

4.1 Description of polar and scatter plots

Although the “absolute” regression coefficients (b_1, b_2, ….b_k in Eq 3-2) were used to estimate the LWD for each site day (where data are available and the regression yields meaningful results), they provide no information on the relative importance of each variable in terms of the contribution to the estimated LWD value. That is, for example, though a specific set of wind conditions may be statistically well-correlated with measured dust concentrations, the occurrence of those conditions may be so infrequent that on the whole, those conditions represent only a negligible contribution to LWD. To better represent the importance of specific wind conditions to the estimated LWD, the independent (G_1, G_2, …G_k) were transformed to a z-score,, with mean of zero and standard deviation of 1. A separate MLRA was completed using these normalized variables and resulting in a set of standardized regression coefficients (β_1, β_2,......, β_n). Whereas the absolute regression coefficients are more useful for estimating the value of LWD for a given site-day, the standardized coefficients provide more insight into the relative importance of specific wind conditions with respect to LWD for all days in the regression. For this reason, this latter set of coefficients was used to construct the polar plots in Figures 1 – 42. Table 6 shows the values of the absolute regression coefficients for each of the 42 sites.

Figures 1 – 42 also show scatter plots of LWD values (screened using the $LWD_j - 2 \cdot E_j \leq 0$ criteria) vs the total measured dust for each IMPROVE site when both IMPROVE aerosol and surface meteorological data were available. IMPROVE data were the measured dust was in the lowest 5^{th} percentile for the year are not included in the figures. Worst dust days are indicated by red triangles. The dashed line in the figures represents where points with a 1:1 correspondence would be located. Moderate-to-high contributions of LWD are represented by data-points located above (upper-left) and near the 1:1 line, while comparatively low contributions of estimated LWD to measured dust are indicated by data-points that lie close to the y-axis. Data-points that are located below the 1:1 line correspond to site days when estimates of LWD exceed the total measured dust (i.e. LWD is overestimated by the regression model.) Two specific example cases are discussed below.

Example 1, Badlands National Park, SD (BADL): The polar plot indicates that three statistically significant variables (wind conditions), namely, WD3WS2-B, WD2WS3-B and WD1WS3-B (where the direction bins in column B of Table 3 were used). According to the plot, the first variable, WD3WS2-B, was the most important contributor ($\beta > 0.35$) to the estimated LWD. The vast majority of the IMPROVE sample days at BADL are located above the 1:1 line. Considering the scatter plot for BADL, for most of non-worst dust days, LWD was accounted for most of the measured dust concentrations as illustrated by the proximity of the blue points to the 1:1 line. For worst dust days, the contribution of local windblown dust accounted for 20 - 50% of measured dust concentrations.

Example 2, Bosque del Apache, NM (BOAP): The polar plot for BOAP shows two statistically significant variables, namely, WD2WS3-A and WD3WS3-A. WD2WS3-A, appeared to be the more important contributor ($\beta > 0.35$) compared to WD3WS3-A. For both non-worst dust days and worst dust days, data-points are on or near the 1:1 line indicating that local windblown dust was the major source of dust.

5. Air masses backward trajectories

Back trajectories going back in time for 2 days were generated for all sites considered in this analysis every 3 hours using the NOAA HYSPLIT trajectory model (Draxler and Hess, 1997) and Eta Data Assimilation System (EDAS) meteorological fields as inputs. For sites in Hawaii and Alaska, hemispheric FNL meteorological fields were used as inputs instead of EDAS. Starting heights for all sites were 500 m above ground level. Back trajectories were useful for two reasons. First, they provided an approximate path for the air mass measured at the site, thereby providing information on potential dust sources that may have been encountered along the way. Second, they provided information on approximate wind speeds along the path of travel. In order to facilitate comparison with the results of the MLRA discussed above, wind speeds calculated from back trajectories were grouped into three categories: (a) Trajectory speed < 14 miles/hour; (b) 14 < Trajectory speed < 20 miles/hour and; (c) Trajectory speed > 20 miles/hour. The utility of these categories in accomplishing the overall goals of this study are discussed in a later section.

6. Land use

The National Land Cover Characterization 2001 (NLCD, 2001) database, covering all 50 states and Puerto Rico, was obtained from the USGS. The database provides a 30 m by 30 m delineation of land use using 19 categories (See Table 7). For the purposes of the present analysis, the 19 categories were further distilled into three major categories:

1. Human-influenced: Land use groups 21, 22, 23, 32, 33, 81, 82, 83, 84 and 85
2. Forests and wetlands: Land use groups 11, 12, 41, 42, 43 and 61
3. Grasslands and shrub lands: Land use groups 31, 51 and 71

Category 1 was intended to represent areas that have been influenced by human activity. This category includes residential/commercial areas, mines and quarries, and agricultural activities. Category 2 includes areas that are forested and therefore very unlikely to be significant sources of windblown dust. Category 3 includes grasslands and shrublands.

Depending on the geographic region being considered, grasslands, especially during long dry periods, could be potential sources of windblown dust. Shrublands are mostly prevalent in the desert southwest and can represent significant source areas for windblown dust.

7. Soil properties – Wind Erosion Group

Windblown dust emission is a complex process that is dependent to varying extents on wind conditions, vegetation (or other) cover, and soil properties. The USGS has mapped the soil characteristics of the United States and based on textural properties has estimated the rates of water and wind erosion that certain areas are likely to experience. For this study, the Wind Erosion Group (WEG) index provided by USGS was utilized to provide a screening level assessment of which parts of the WRAP region – or areas upwind – are potentially large contributors to measured dust concentration through the wind erosion process. The WEG number ranges from 1 to 8, with 1 representing the most erodible soil types and 8 representing the least erodible soil types. WEG data for 48 US states were downloaded from USGS Water Resources (Table 8). While WEG data can be helpful, it is important to keep in mind that the WEG index only provides an approximate categorization of soil types with respect to their erodibility under a specific set of conditions. The presence or absence of vegetative cover, a surface crust, or mitigating topography can greatly influence actual wind erosion and dust emission rates. Thus, in order to make use of the information provided by the USGS soil database, it is important to combine the WEG with information on land use.

The WEG index (spanning the range 1 – 8) was reduced to three categories. The first encompassing WEG numbers from 1-3 corresponds to soil textures that are likely to result in high dust emissions. The second category corresponds to soil textures with intermediate inherent wind erodibility (4-6). The third category corresponds to soil textures least likely to be subject to wind erodibility (6-8). Using this revised wind erodibility measure, the three categories were spatially combined with the three land use categories (human-influenced, forest and wetlands, and shrub and grasslands) to yield a total of 9 possible combinations. The resultant WEG/Landuse data base was used as the background for all GIS analyses.

8. Integration into ArcGIS – Data analysis

For this study, the tools discussed previously including MLRA, Asian dust score, back trajectories, and soil and land use databases served as input information for the primary tool used in completing this analysis, a geographic information system (GIS) rendering of all the separate components. Viewed in unison, these tools provided the means for heuristic and semi-quantitative analysis of the causes of dust-resultant haze on the worst dust days at sites within the WRAP.

For every worst dust at each of the 71 sites considered over the 2001-2003 period, a map was generated containing the following components (when data were available):

1. An indicator of the Asian dust score at that site
2. An indicator of the ratio of LWD to measured dust
3. Three back trajectories (with trajectory points coded for wind speed) corresponding to start times of 8:00 AM, 2:00 PM, and 8:00 PM (Central Standard time for all sites)

For sample days where there were multiple sites experiencing worst dust days, data for all of those sites was displayed on the same map.

Since this analysis is inherently non-quantitative, an event type was associated with every worst dust days with a specification of the level of confidence in the association. The event types were: Asian dust event, windblown dust event, transport of dust from upwind of the site, and "undetermined" event. The undetermined event signifies that insufficient information was available to determine the primary cause of the worst dust day. Windblown events were further associated with a gauge of the scale of the event.

The degree of confidence in an event specification for a given worst dust day was specified using five "+" signs. For worst dust days where the event type was identified with a high degree of confidence, five "+" signs were assigned to that event type. For days when the confidence in the event was lower, fewer "+" signs were assigned to the suspected event that caused the dust and the remainder (total of five) were assigned to the "undetermined" event category. On days where there was insufficient evidence for even a low confidence guess, all five "+" signs were placed in the "undetermined" event category. The criteria shown in Table 9 were used as guidelines for determining the best category and level of confidence for each worst dust day and not as a rigid decision tree. In some cases, experience gained through the process of reviewing the 644 worst dust days provided better direction than the actual numbers (e.g. Asian dust score) associated with the worst dust day at a given site. An effort was made to keep those “professional” judgments to a minimum. Figure 43 shows the legend of ths layers used to develop the maps. An example of a map is illustrated at Figure 44.

9. Example Case studies

9.1 April 16, 2001 (20010416)

On April 16, 2001, 29 sites were classified as worst dust days. For 22 sites, the Asian Dust Score was higher that 1500, indicating a strong Asian signature. Satellite and Naval Research Laboratory model results corroborated a large Asian dust plume engulfing a large portion of the West coast. Thus, the worst dust days for those 22 sites were surmised to be caused by an Asian dust event with a confidence level of +++++.

Though the LWD factor for Bliss State Park constituted 5.7% of the total measured dust, that site provided a very high Asian Dust Score (624741) combined with the large number of surrounding sites affected by Asian dust with high confidence. Therefore, according to the criteria in Table 9, the worst dust day at Bliss State Park was associated with the Asian Dust event with a confidence level of +++. Similar reasoning was used to assign Lava Beds (LABE), Ike’s Backbone (IKBA), Mesa Verde (MEVE), and Brooklyn Lake (BRLA) to an Asian dust event with confidence level of +++. These sites illustrate cases were professional judgment was used. Though Asian Dust Scores were less than 1500, the clear eveidence of strong Asian Dust influence over the western US combined with lack of substantial evidence that another event (e.g. windblown dust) resulted in exceptions to the guidelines shown in Table 9.

Salt Creek (SACR) showed only a moderate Asian Dust Score, but a LWD to total dust ratio >0.5. In addition, back trajectories indicate high winds near SACR over fairly erodible terrain. Thus, the worst dust day at SACR was associated with windblown dust (confidence +++++). Since it is the only site in the area with windblown dust effects, the event was not deemed to be of regional scale. At Guadalupe Mountains, (GUMO), surface meteorological data indicated that winds at the site were not of sufficient force to cause windblown dust to an appreciable degree (LWD = 0). Back trajectories indicated that high winds were possible over portions of Mexico. However, those high winds had occurred more than 24 hours prior to the worst dust day at GUMO and soil erodibility information for Mexico was not available for this study. Therefore, GUMO was completely undetermined for this worst dust day (i.e. undetermined +++++).

9.2 September 10, 2001 (20010910)

On September 10, 2001, 5 sites located in Arizona were classified as worst dust days. For all sites, the ADS was low (or not calculated), suggesting a negligible contribution of transported Asian dust. Local windblown dust was only estimated (by MLRA) in SAGU (LWD=60.7%). SAGU was associated with windblown dust with a confidence of +++++ but the event was not deemed regional. Trajectory analysis for all sites indicated moderate-to-high speed trajectories over areas with moderate-high erodibility in southeast Arizona, south New Mexico and east/southeast Texas. IKBA and SIAN were associated with upwind transport with a confidence level of +++ (more than 8 hours spent at high wind). CHIR was also associated with upwind transport but at a confidence level of + (more than 3 hours spent over erodibile land). SYCA likely also experienced upwind transport (based on confidence level +++ at IKBA and SIAN), but the absence of surface met data did not allow for exclusion of windblown dust. Therefore, SYCA was associated with upwind transport at a confidence level of +.

9.3 July 06, 2001 (20010706)

On July 06, 2001, 4 sites were classified as worst dust days. At Colombia River Gorge (CORI) the LWD to Total measured dust ratio was 40.5%. However, back trajectories did not show sustained high winds over moderately (or highly) erodible terrain. Thus, CORI was assigned to a windblown event at a confidence level of +. At Bandalier (BAND) the LWD to total measured dust ratio was ~ 6% and trajectories showed some high winds over moderately erodible terrain. BAND was associated with windblown event with a confidence of +. The information available for Nearby San Pedro (SAPE) And Gila (GICL) did not provide any indication of the event that may have caused a worst dust day there (undetermined +++++).

9.4 April 03, 2003 (20030403)

Great Sand Dunes (GRSA), Weminuche Wilderness (WEMI), and Rocky Mountain (ROMO) had worst dust days on April 03, 2003. Back trajectories for all three sites showed high winds over erodible land upwind of the sites. At GRSA, and WEMI, the LWD to total measured dust ratios were > 0.25 and > 1 respectively. At ROMO, no LWD was estimated for the wind conditions there. Based on these observations, GRSA was associated with windblown dust (confidence +++++), WEMI was associated with windblown dust (confidence +++), and ROMO was associated with transport from upwind (confidence +++). For all three sites, the event was flagged as a regional scale event since the same general flow pattern caused all three sites to have worst dust days.

10. References

Cheng, TT, Lu, DR, Wang, GC, Xu, YF. Chemical characteristics of Asian dust aerosol from Hunshan Dake sandland in Northern China. Atmospheric Environment, 2005. 2903-2911

Darmenova, K, Sokolik, IN, Darmenov, A. Characterization of east Asian dust outbreaks in the spring of 2001 using ground-based and satellite data. Journal of Geophysical Research, 2005 D02204

Draxler, R.R. and G.D. Hess, 1997, Description of the Hysplit_4 modeling system, NOAA Tech Memo ERL ARL-224, Dec, 24p

Park, SU, Chang, LS, Lee, EH. Direct radiative forcing due to aerosols in East Asia during a Hwangsa(Asian dust) event observed on 19-23 March 2002 in Korea. Atmospheric Environment, 2005, 2593-2606

Perry KD, Cahill TA, Eldred RA, Dutcher DD, Gill T, 1997, Long-range transport of North African dust to the eastern United States Journal of Geophysical Research 102 (D10): 11225-11238

VanCuren RA, Cahill TA Title: Asian aerosols in North America: Frequency and concentration of fine dust. Journal of Geophysical Research 107 (D24): Art. No. 4804 DEC 28 2002

Zhang, RJ, Arimoto, R, An, JL, Yabuki, S, Sun, JH. Ground observations of a strong dust storm in Beijing in March 2002. Journal of Geophysical Research, 2005, D18S06