Atmospheric bioaerosols transported via dust storms in the western United States

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[1] Measurements are presented showing the presence of biological material within frequent dust storms in the western United States. Previous work has indicated that biological particles were enhancing the impact of dust storms on the formation of clouds. This paper presents multiple case studies, between April and May 2010, showing the presence of and quantifying the amount of biological material via an Ultraviolet Aerodynamic Particle Sizer during dust events. All dust storms originated in the Four Corners region in the western Untied States and were measured at Storm Peak Laboratory, a high elevation facility in northwestern Colorado. From an Aerodynamic Particle Sizer, the mean dust particle size during these events was approximately 1 μm, with number concentrations between 6 cm^{-3} and 12 cm^{-3}. Approximately 0.2% of these dust particles had fluorescence signatures, indicating the presence of biological material.
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1. Introduction

[2] Aerosols affect the Earth's radiation balance directly by scattering sunlight; modifying the duration of snow and ice through atmospheric heating [*Ramanathan et al.*, 2007] and albedo decreases [e.g., *Painter et al.*, 2007]; and indirectly through their role as either cloud condensation nuclei or ice nuclei [e.g., *Twomey*, 1974; *Chuang et al.*, 1997]. The role of aerosols on clouds represents the largest uncertainty in climate change models and predictions. Current estimates of the effect of aerosols on clouds (−1.8 to −0.3 W m^{-2}) remain uncertain because of our inability to accurately estimate the spatial and temporal distributions of aerosol concentrations, size, and composition, and effect on both water and ice clouds [*Intergovernmental Panel on Climate Change*, 2007]. Specifically, *Fridlind et al.* [2007] has shown that ambient ice nuclei appear insufficient by a few orders of magnitude to explain observed ice in the atmosphere, consistent with past literature [e.g., *Hobbs and Alkezweeny*, 1968; *Beard*, 1992]. One potential explanation for this discrepancy may be the role of bioaerosols as ice nuclei. Bioaerosols are defined as organic aerosols that are alive, carry living organisms, or are released from living organisms. Examples of bioaerosol include bacteria, fungi, viruses, pollen, cell debris, and bio-films, ranging in size between 10 nm and 100 μm [*Ariya and Amyot*, 2004]. Previous microbiology work [*Griffin*, 2007, and references within] has illustrated the diverse community of bacteria, fungi, and viruses present within airborne dust.

[3] As reviewed by *Diehl and Wurzler* [2010], many laboratory studies have investigated ice-nucleating abilities of bioaerosols [e.g., *Levin and Yankofsky*, 1983; *Diehl et al.*, 2002] and have generally observed freezing temperatures higher than those of typical ice nuclei such as mineral dust and soot [e.g., *DeMott*, 1990; *Diehl and Mitra*, 1998]. A recent modeling study by *Diehl and Wurzler* [2010] looked at the effect of bacteria acting as immersion ice nuclei. The study stated that "even diminutive amounts of bacteria could affect cloud ice microphysics and hence, they should not be neglected against other ice nuclei such as mineral dust and soot particles." Recent results via the ICE-L field campaign over Wyoming demonstrated biological particles mixed with mineral dust initiated ice formation, and led to the conclusion that biological particles were enhancing the impact of dust storms on the formation of clouds [*Pratt et al.*, 2009].

[4] Human activities such as livestock grazing have increased dust in the western interior United States by disturbing natural, stable surfaces such as cryptobiotic soils and physical crusts in the extensive deserts [*Belnap and Gillette*, 1998; *Reynolds et al.*, 2001]. With sediment cores from two alpine lakes in the San Juan Mountains of southwest Colorado by *Neff et al.* [2008] showed that dust accumulation rates over the last 150 years are more than five times greater than the average accumulation over the previous 5,000 years. Based on ensemble backtrajectories, geostationary remote sensing data, and the size of these dust particles extracted from snow (i.e. greater than 10 microns), the dust appears to be predominately from the western United States. The Upper Colorado River basin currently experiences four to twelve large winter- and spring-time dust deposition events each year [*Neff et al.*, 2008]. These increasing dust storms have large implications for the regional snowpack in the Upper Colorado River Basin and its runoff by shortening seasonal snow coverage [*Painter et al.*, 2007, 2010]. This study provides a direct link between these regional dust storms and bioaerosols traveling with the dust.

[5] In the last few years, ultraviolet fluorescence has been added to *in situ* aerosol instrumentation for the real-time detection of bioaerosols [e.g., *Huffman et al.*, 2010]; an

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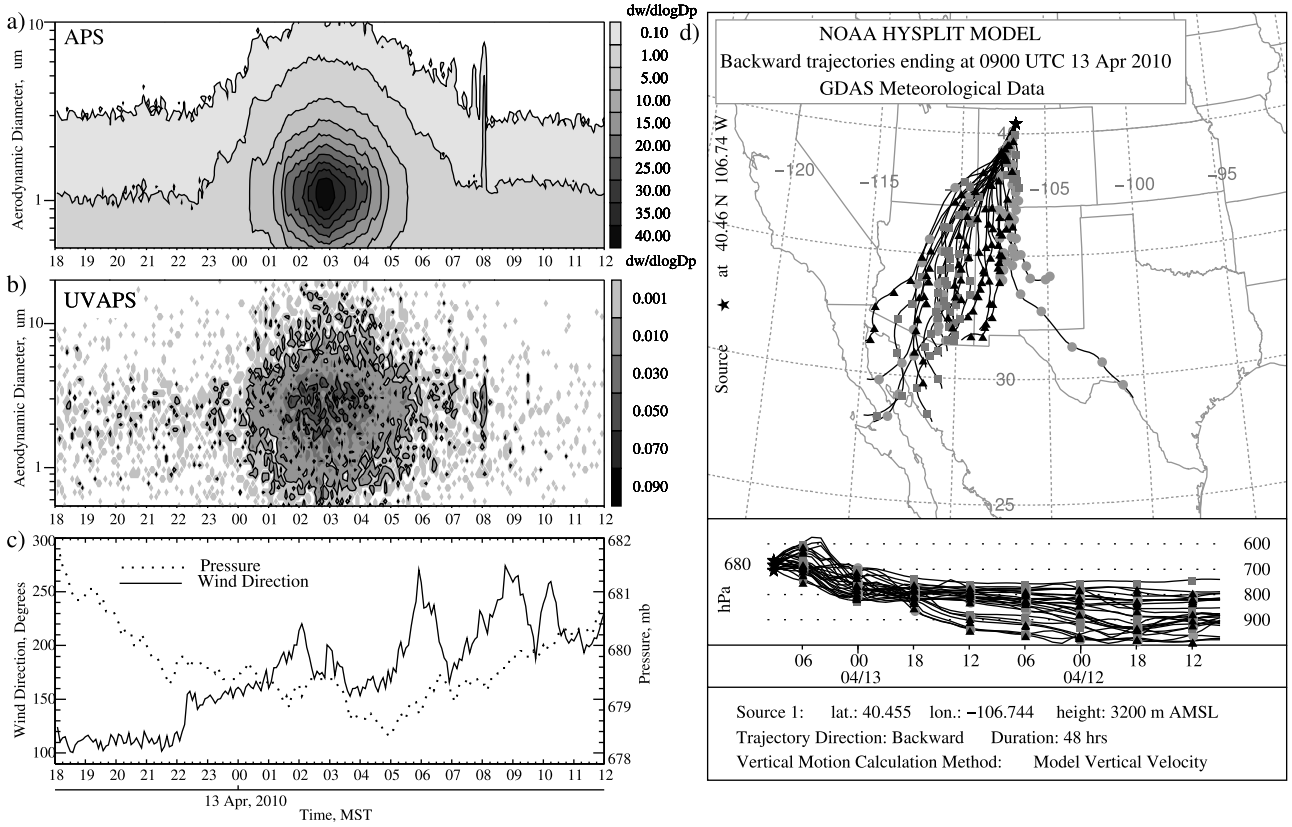

Figure 1. Figures 1a–1c represent a times series of data covering case study 1. (a) The APS particle size distributions as a concentration matrix, with the x-axis representing the particle size and the colors represent the normalized concentration (dw/dlogDp). Here dw is the number of particles in the range (total concentration) and dlogDp is the difference in the log of the channel width. (b) Fluorescence biological particle size distribution from the UV-APS. (c) The meteorological conditions (pressure and wind direction) during the case study. (d) An ensemble HYSPLIT backtrajectory from SPL for the center (02:00 MST) of this event.

example of this instrumentation is the Ultraviolet Aerodynamic Particle Sizer (UV-APS). To better constrain our understanding of the transport mechanisms of bioaerosols within dust storms in the western United States, a UV-APS was deployed at Storm Peak Laboratory from late winter through early summer of 2010. We describe these results below.

2. Methods

[6] This study utilized both an APS (TSI Inc, Model 3321) and a UV-APS (TSI Inc, Model 3314, Minneapolis, MN), both of which measure particles with an aerodynamical diameter between 0.54 and 19.81 microns. Both in the APS and UV-APS, aerodynamic particle size was measured from the time of flight of the particle between two (633 nm) He-Ne lasers. Additionally in the UV-APS, an ultraviolet laser (355 nm) excites the aerosols resulting in fluorescence in wavelength range of 420–575 nm; this is a signature characteristic for reduced pyridine necleotides and for riboflavin and thus specific to living cells. The UV-APS design, along with a performance evaluation, is described in detail by *Brosseau et al*. [2000], *Agranovski et al*. [2003], and *Huffman et al*. [2010]. These instruments were deployed at Storm Peak Laboratory between February 2, 2010 and June 23, 2010. Within this paper, we will refer to events with sustained (i.e. lasting over one hour) total concentrations greater than 1 cm^{-3} for aerosol sizes above 2.5 μm as dust events.

3. Location and Facility

[7] Storm Peak Laboratory (SPL, 3210 m asl), operated by the Desert Research Institute (DRI), is located on the west summit of Mt. Werner in the Park Range near Steamboat Springs in northwestern Colorado. This site has been used in cloud and aerosol studies for more than 25 years [e.g., *Hallar et al*., 2011; *Borys and Wetzel*, 1997]. SPL is situated on a 70 km long north-south mountain barrier, oriented generally perpendicular to the prevailing westerly winds. The facility is located on a peak with limited upwind vegetation or topography to create local turbulence under normal airflow conditions. SPL experiences transport from distant continental sources including urban areas, power plants, and wildfires, along with intercontinental dust from Asia [*Obrist et al*., 2008]. As standard at mountain top locations, SPL experiences upslope winds typically mid-day and clean nighttime conditions [*Obrist et al*., 2008]. Particles at SPL are sampled from an insulated, 15-cm diameter manifold within approximately 1 m of its horizontal entry point through an outside wall. The 4 m high vertical section outside the building is capped with a heated inverted can. This aerosol manifold has approximately a flow of 500 L min^{-1} and a 50% cut-off at

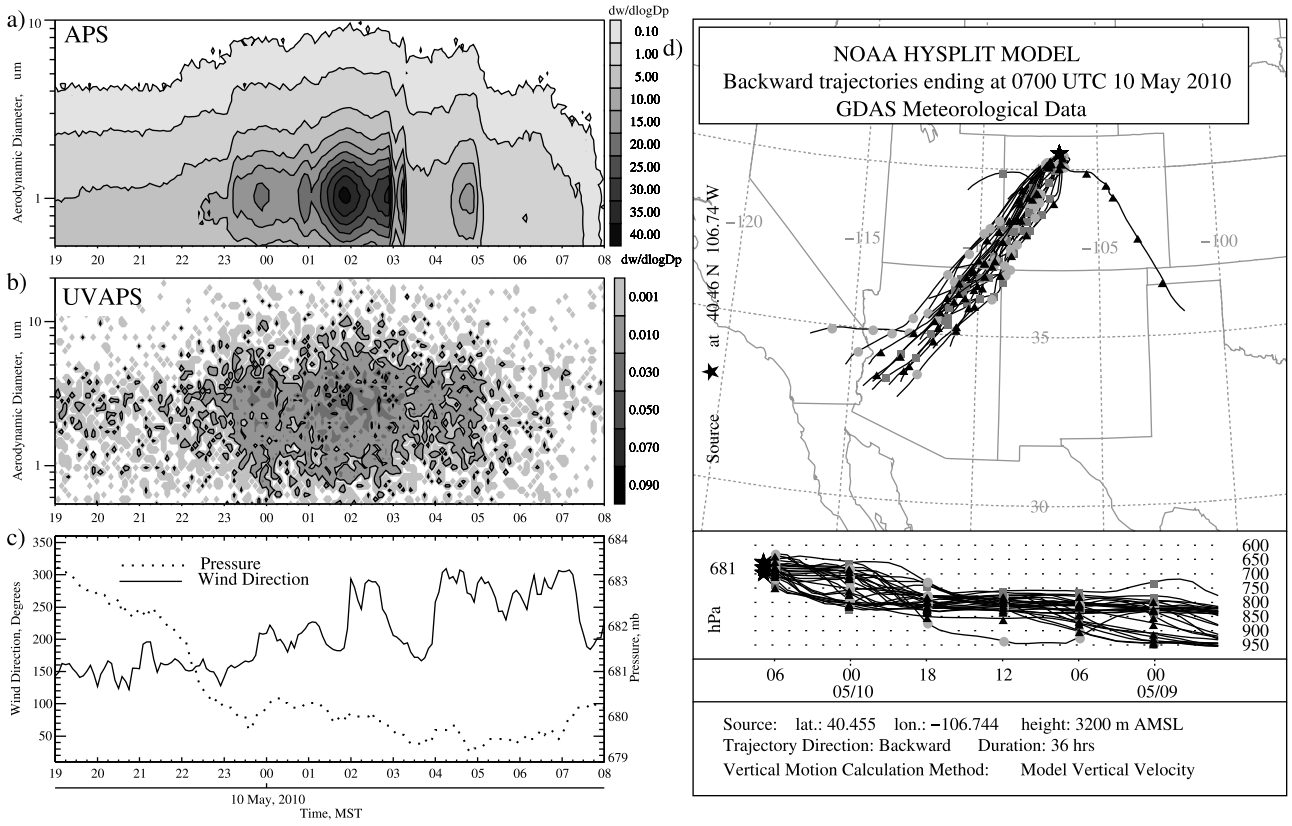

Figure 2. Figures 2a–2c represent a times series of data covering case study 2. (a) The APS particle size distributions as a concentration matrix, with the x-axis representing the particle size and the colors represent the normalized concentration (dw/dlogDp). (b) Fluorescence biological particle size distribution from the UV-APS, also as a concentration matrix. (c) The meteorological conditions (pressure and wind direction) during the case study. (d) An ensemble HYSPLIT backtrajectory from SPL for the center (00:00 MST) of this event.

a particle size of 5 microns. Both the APS and UV-APS instruments were attached to the aerosol manifold using 0.75 in conductive tubing and had a 1 L min^{-1} sample flow rate. Both the APS and UV-APS were placed at the same point on the aerosol manifold and care was taken to avoid any horizontal tubing between the aerosol manifold and the instruments.

4. Data Processing

[8] Following the methodology of *Huffman et al*. [2010] and *Agranovski et al*. [2004], number size distributions of fluorescent aerosol particles $dN_f/dlogD$ were calculated for each size bin from the sum of the particle number concentrations in fluorescence channels 3-64. This methodology represents a lower limit for the actual abundance of primary biological aerosol particles [*Huffman et al*., 2010]. All analysis of the APS and UV-APS includes size bins 2-64; the first bin representing particles below 0.54 μm was not included.

5. Calculations of Air Mass Trajectories

[9] NOAA Hybrid Single-Particle Lagrangian integrated trajectories (HYSPLIT, http://www.arl.noaa.gov/ready/hysplit4.html; http://www.arl.noaa.gov/ready/hysplit4.html) were calculated for specific dates to determine the origin of air masses measured at SPL. In this study, 36 or 48 hour backtrajectories were calculated in ensemble forms that calculate 27 trajectories from a selected starting point (i.e. receptor in the model parlance). Each member of the trajectory ensemble is calculated by offsetting meteorological data by one meteorological grid point (1 degree) in the horizontal (both latitudinal and longitudinal) and 0.01 sigma units (250 m) in the vertical for the selected starting point. HYSPLIT was run with the National Centers for Environmental Prediction's (NCEP) Global Data Assimilation System (GDAS) data set. More information on this data set can be found at http://www.emc.ncep.noaa.gov/gmb/gdas/. The computational height was selected between 680 and 690 mb, based on the height that most closely represents the common pressure at the lab during this time period.

6. Results

[10] Below, we present three case studies that occurred between April 12 and May 24, 2010. These illustrate that dust storms originating in the Four Corners region in the western United States (intersection of Colorado, Utah, New Mexico, and Arizona) contain bioaerosols. All dust cases occurred during the nighttime hours, when it is expected that the air masses at the SPL are more regional, and thus less impacted by the local boundary layer. These events at SPL are consistent with dust events D5 (April 12–13), D7 (May 9), and D9 (May 22) that were documented at Senator Beck

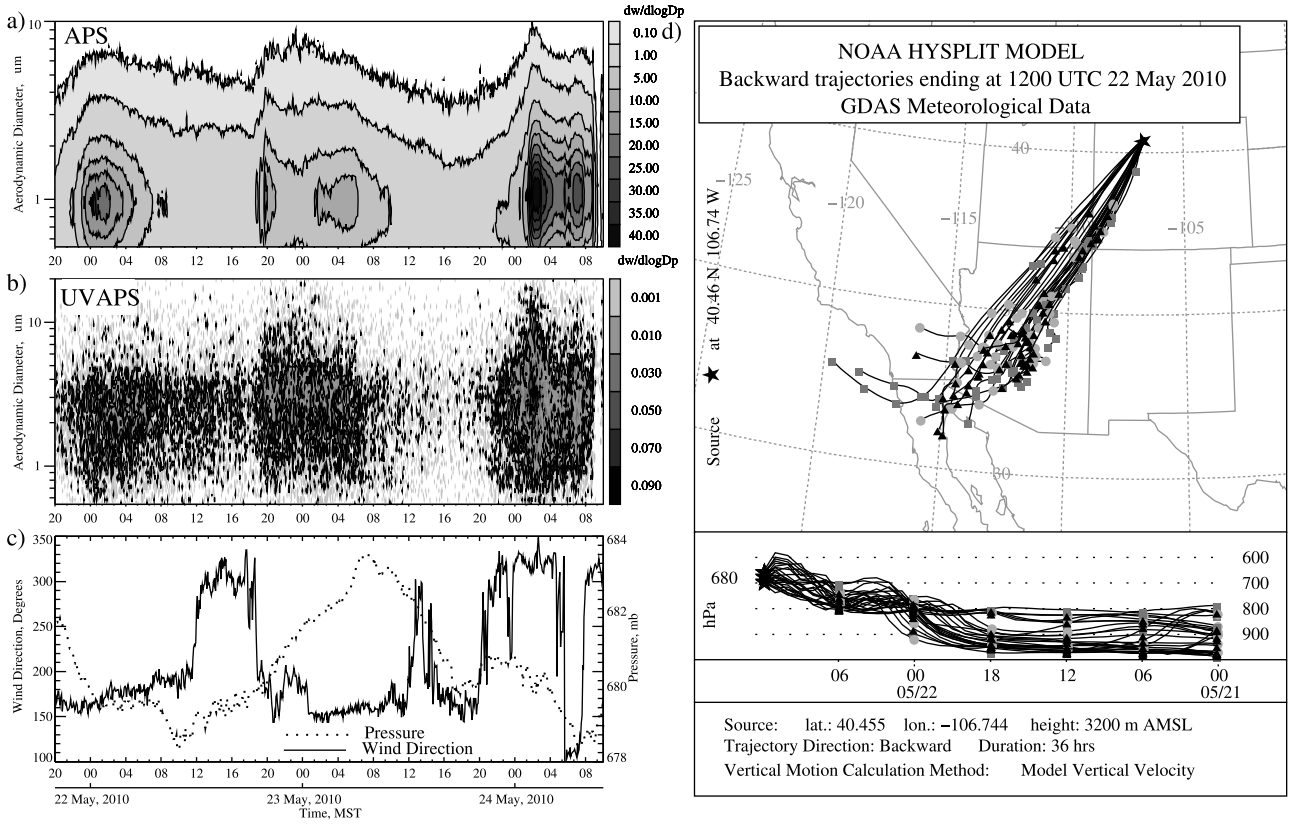

Figure 3. Figures 3a–3c represent a times series of data covering case study 3. (a) The APS particle size distributions as a concentration matrix. (b) Fluorescence biological particle size distribution from the UV-APS, also as a concentration matrix. (c) The meteorological conditions (pressure and wind direction) during the case study. (d) An ensemble HYSPLIT back-trajectory from SPL for this event (centered on May 22, 05:00 MST).

Basin Study Area in the San Juan Mountains, Colorado by the Center for Snow and Avalanche Studies (www.snowstudies.org) as part of the Colorado Dust on Snow monitoring program. It should be noted that there is a potential fluorescence signatures from Kaolin [*Huffman et al*., 2010], yet as shown by [*Lawrence et al*., 2010] aeolian dust from the Four Corners region has only traces of Kaolin (1.7 ± 0.9 percent by weight).

6.1. Case 1: April 13, 2010

[11] As shown below in Figure 1a, aerosols with a size distribution extending to 8 μm were observed at Storm Peak Laboratory using the APS on April 13 centered at approximately 03:00 MST. This event lasted five hours, starting at 00:30 and ending at 05:30 MST. The mean number concentration for the APS was 12.4 ± 6.5 cm^{-3} during this period. The mean diameter of these aerosols was 1.24 ± 0.01 μm. This particle size is consistent with previous studies demonstrating regional dust events. For example, *Raabe et al*. [1988] and *Cahill and Wakabayashi* [1993] reported that North American dust is almost entirely in the size range between 1.5 and 2.5 μm. Simultaneously, the UV-APS also observed a fluorescence signal indicating the presence of biological material, as shown in Figure 1b. The UV-APS mean number concentration was 0.03 ± 0.01 cm^{-3}, representing approximately 0.2% of the total aerosol concentration. In comparison, this concentration of fluorescent biological aerosol particles is very similar to those reported with a 5-month study in Mainz, Germany [*Huffman et al*., 2010], although the total particle concentration reported here is much higher. The *Huffman et al*. [2010] study looked only at particles greater than 1 μm, where this study includes particles greater than 0.5 μm. The wind direction during this period was shifting from the south (180°) to the west (270°), as illustrated in Figure 1c. A 48-hour back trajectory for this scenario (Figure 1d) was created using HYSPLIT. As shown by the convergence of the ensemble, air from the southwest consistently reaches SPL around 2:00 MST on April 13 (09:00 UTC). These back trajectories also indicate that the air is in contact with the ground surface in the vicinity of northern New Mexico and Arizona approximately 36 hours before reaching SPL.

6.2. Case 2: May 9–10

[12] Aerosols larger than 6 μm were observed on May 10 with an event centering on 02:00 MST. As shown in Figure 2a, dust was observed at SPL between 19:00 MST on May 9 and 08:00 MST on May 10. The mean number concentration for the APS was 6.3 ± 5.2 cm^{-3} during this period. The mean diameter of these aerosols, during this period was 1.06 ± 0.09 μm. Simultaneously, the UV-APS also observed a florescence signal indicating the presence of biological material, as shown in Figure 2b. The UV-APS mean number concentration was 0.01 ± 0.01 cm^{-3}, representing approximately 0.2% of the total aerosol concentration. Similar to case 1, the wind direction was steadily shifting in direction

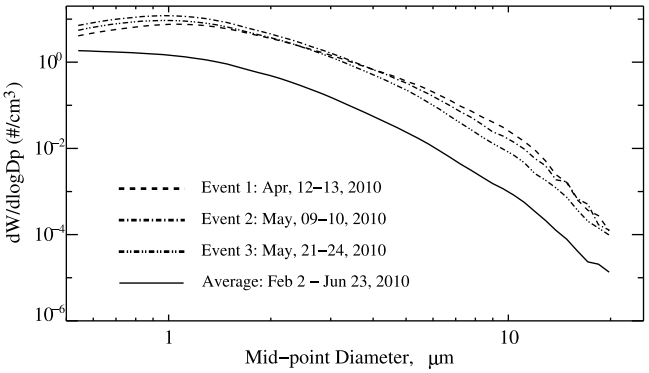

Figure 4. Illustration of the aerosol size distribution from the APS for all three events described (shown with the dashed lines), and are clearly distinct from nominal conditions (shown with the solid line).

from the south to the west (Figure 2c). A 48-hour back trajectory for this case (Figure 2d) was created using HYSPLIT. Air from the southwest consistently, as shown by the convergence of the ensemble, reaches SPL at 24:00 MST on May 9 (07:00 UTC on May 10). The back trajectory shown in Figure 2d indicates that the air is in contact with the ground surface in the vicinity of northern Arizona approximately 23 hours before reaching SPL.

6.3. Case 3: May 21–24, 2010

[13] The final case study looks at three dust events, associated with UV florescence, between May 21 and May 24, 2010, shown in Figures 3a and 3b. As demonstrated previously, these are also nighttime events. During the dust observations on May 22 and May 23, the wind was predominantly from the west. Yet on May 24, a southerly wind direction was associated with the dust (Figure 3c). Back trajectories during all three nights show a predominate flow from the southwest originating in the Four Corners region (example shown in Figure 3d).

[14] The time averaged size distributions were similar for cases 1, 2, 3, as illustrated in Figure 4. Additionally, these times periods are distinct from nominal conditions observed at SPL.

7. Discussion

[15] The observations made during the spring season at the SPL show a strong relationship between airborne concentrations of large particles, assumed to be dust, and particles with biological origins. The observations indicate that the source of the dust observed is in the southwestern United States, consistent with the observations and modeling in the San Juan Mountains [*Painter et al.*, 2007]. The corresponding elevated concentrations of bioaerosols and dust provide evidence that bioaerosols are lofted in conjunction with dust particles to the atmosphere. Soils in the Four Corners region were known to be covered by cryptobiotic crust containing cyanobacteria, fungi, lichen, and moss [*Munson et al.*, 2011]. However, the vast land disturbance of the late 1800s to present day has eliminated much of the mature state of cryptobiotic soils and replaced it with less stable surfaces with depleted nutrients [*Neff et al.*, 2005]. Because dust can act as ice nuclei, and further, some bioaerosols have been shown to also act as ice nuclei, the elevated concentrations of these atmospheric constituents could have important impacts on cloud formation and characteristics in the atmosphere. The evidence from these observations are consistent with others [*Pratt et al.*, 2009], and suggests the need to better characterize the biological component of larger particles in the atmosphere, and further, their impact of aerosol-cloud processes.

[16] Based on the new understanding of the impact of dust on the acceleration of snowmelt and reduction of runoff from the Upper Colorado River [*Painter et al.*, 2007, 2010], water and land managers in the region are pursuing mitigation of dust emission to reduce this impact. Critical to this effort however is the capacity to better identify dust sources and in turn connect them to the associated disturbance, whether previous or ongoing. The capacity to detect varying concentrations of bioaerosols may provide additional capacity to identify provenance and contributing processes.

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