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CONDENSATION NUCLEUS, SO_2 AND NO_2 CONCENTRATIONS IN AIR ARRIVING AT STORM PEAK LABORATORY, COLORADO DURING AN EAST-WIND EVENT

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1. INTRODUCTION

From 11 to 25 January 2001, a group of students and staff from The City College of New York (CCNY) and Bronx Community College (BCC) traveled to Storm Peak Laboratory (SPL) as part of an environmental field studies course (Hindman, 1993; Hindman, 2001). Located at the 10,500ft (3200m) west summit of Mt. Werner on the Steamboat Springs ski area in the northern Colorado Rockies (40.48N, 106.72W), SPL provides an ideal location to perform meteorological and atmospheric experiments at high elevation (Borys and Wetzel, 1997). During the two-week study, students collected weather data, condensation nucleus (CN), sulfur dioxide (SO_2) and nitrogen dioxide (NO_2) concentrations in both clear and cloudy conditions.

SPL is located atop the 70 km long, north-south Park Range, and is generally oriented perpendicular to the prevailing westerly winds. In winter the laboratory is frequently immersed in snowing, supercooled clouds (Ponce and Hindman, 2001). However, from 0900MST, 15 January to 1300MST, 18 January 2001, SPL experienced a period of clear air. During much of this period, there was distinct wind from the east. The east wind was unusual given that the prevailing winter weather pattern at SPL is usually dominated by westerly winds (Rauber, et al., 1986).

Borys, et al., (1986) investigation of an east-wind event offers possible explanations of what we observed at SPL in January 2001. They found a combination of the development of a lee-side low east of the Rockies, moisture from the Gulf of Mexico and shallow, cold polar air masses may lead to persistent, large-scale easterly flow near the surface which can bring air to Colorado from distant sources in the east. This airflow likely contributed to the observed east-wind pattern at SPL. We studied these patterns to determine the extent to which this east wind may have contributed to air pollution found at SPL.

2. OBJECTIVES

This paper presents an analysis of the air parcel trajectories arriving at SPL during an east-wind event in January 2001 and offers a determination of the source regions(s) and source strengths of the air. It also provides information and an explanation of CN, SO_2 and NO_2 concentrations in the air arriving at SPL.

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3. MEASURMENTS

To measure atmospheric conditions, students conducted weather observations (eg., cloud type, visibility and precipitation) every four hours and meteorological measurements (eg. air temperature, relative humidity, wind direction/speed and air pressure) were measured every 5 minutes with an automatic weather station. Additionally, CN were measured using TSI 3025 and 3010 condensation nucleus counters (www.tsi.com) with particle diameter thresholds of, respectively, 0.003 and 0.01 μm. Measurements from the TSI 3025 are called ultrafine CN and measurements from the TSI 3010 are called CN. The CN data were averaged and recorded every 5 minutes on a Campbell Scientific CR10 data logger.

Students performed experiments to test for the presence of SO_2 and NO_2 every four hours at SPL (and at SPL Base in the valley below). The first experiment tested for the existence SO_2 using the West-Gaeke method (West and Gaeke, 1956). Outside air was bubbled through a scrubber containing sodium tetrachoromercurate for 30 minutes, forming the stable, nonvolatile dichlorosulfitomercurate. Pararosanline and formaldehyde, then, were added to the scrubbing solution to confirm the presence of SO_2. Spectrophotometric measurements were used to quantify the amount of SO_2.

While the test for SO_2 was underway, the concentration of NO_2 was measured. Measurements were taken using the Griess-Saltzman method (Saltzman, 1954). Outside air was bubbled into a scrubber containing azo dye absorbing solution for 15 minutes and the solution was measured using a spectrophotometer to determine the concentration of NO_2.

Additionally, ozone (O_3) was measured using the SPL ozone monitor (MAST-727-3). Ozone concentrations were recorded continuously on the CR10 data logger.

4. PROCEDURES

To determine the source(s) of the east wind during the clear-air period at SPL, several different Internet meteorological investigations were performed.

To locate the air mass origins, back trajectory analysis were performed. Back trajectories were generated using the National Oceanic and Atmospheric Administrations (NOAA) Hybrid Single-Parcel Integrated Trajectories (HY-SPLIT) model at

www.arl.noaa.gov/ready.html. This process identified an air parcel's location prior to its arrival at SPL (Fig. 1). Seventy-two hour back trajectories were generated and downloaded for each observation time during the clear-air period. Each 72-hour back trajectory had a corresponding text file that contained the parcel's latitude, longitude and elevation for each hour of travel.

For the purpose of comparing the trajectory of each air parcel, the trajectories were plotted using the global-information-system (GIS) application ArcView. Following a procedure developed by Meyer (2000) and simplified by Dias (2001), trajectory text files were reduced to time, latitude, longitude and elevation and loaded into ArcView. A plot, then, was made showing the back trajectories for each observation time during the clear-air period on one screen (Fig. 2).

To further understand the meteorology of the clear-air period, 700 mb streamline and geo-potential height plots were generated and downloaded using the NOAA-ARL archived meteorological products web site at www.arl.noaa.gov/ready/amet.html. These images were located in the Eta Data Assimilation System (EDAS) analysis map archive. Figure 3 is a representative streamline and geo-potential height image downloaded from this site for 17 January 2001 during the east-wind event.

Although it was not precipitating at SPL, further investigations were conducted to test for the existence of any precipitation along the path of the air parcels. This process allowed a determination whether any CN, SO_2 and NO_2 scavenging by cloud and precipitation took place. Radar images corresponding with each hour of every 72-hour back trajectory were downloaded from the NOAA/NCDC web site at ncdc.noaa.gov/ol/radar/radarresources.htlm. For example, Figure 4 illustrates regions of precipitation detected by radar. The hourly radar images, then, were compared to a representative trajectory from each source region to determine if the air parcel encountered precipitation en-route to SPL.

The SO_2, NO_2 and CN concentrations of the air arriving at SPL for each trajectory were determined as follows. The air was bubbled for a period of 30-minutes for SO_2 and, within that period, the NO_2 bubbler was operated for 15 minutes. So, the CN concentrations corresponding to the 30-minute period were averaged to produce a representative CN concentration to pair with the SO_2 and NO_2 concentrations.

5. RESULTS

The streamline and geo-potential height analyses (Fig. 3) shows a region of low pressure south of SPL accounting for the east wind. This low gradually swung eastward "beneath" SPL causing the east winds to gradually "back" from the west-to-southwest sector to the north-to-northwest sector.

The back trajectory analyses of air arriving at SPL revealed three distinct source regions as illustrated in Figure 5. Air arriving at SPL between 0900MST and 2100MST, 15 January (a 12-hour period) originated from a west to southwest source region. Air arriving between 0900MST, 16 January and 1300MST, 17 January (a 28-hour period) originated from an east source region. Air arriving at SPL between 1700 MST, 17 January to 1300MST, 18 January (a 20-hour period) came from a north to northwest source region.

Statistical analyses were conducted on the CN, SO_2 and NO_2 concentrations measured at SPL for air arriving from each source region. Means, standard deviations and standard errors were calculated for the air arriving from each source region (Table 1).

Significant differences were found between the air arriving from the different source regions (Table 1); two means are significantly different when the uncertainties of the means do not overlap. The highest concentrations of CN were in the air arriving from the east source region while the west to southwest source region produced the highest concentrations of NO_2 and SO_2. The O_3 concentrations from each region were found to vary only slightly.

To estimate the CN, SO_2 and NO_2 source strength of each source region, the population per square mile were calculated from 2000 census data (www.census.gov). The population densities are listed in Table 2. The east source region of eastern Colorado had the highest concentration of people per square mile, mainly from the Front-Range cities. The west to southwest region of western Colorado, Utah, Nevada and Arizona was second with the population centers of Salt Lake City, Las Vegas and Phoenix. The most sparsely populated was the north to northwest region of Montana and Wyoming with no major population centers. Surprisingly, the population in the west to southwest region was significantly greater than that of the east region, but the east region had a much smaller area, thus a higher population density.

Visual analysis of the radar images and the corresponding trajectories showed the air parcels encountered little precipitation on their journey to SPL. For the west to southwest and north to northwest source regions, the trajectory–radar analysis showed that the parcels encountered no precipitation en route to SPL. The representative east source region trajectory ending on 0500MST, 17 January encountered precipitation for a 9-hour period (2300MST, 15 January to 0800MST, 16 January 16). Figures 6 shows the position of the air parcel when it initially encountered the precipitation.

6. DISCUSSION

The largest CN concentrations arrived from the east source region (Table 1). Importantly, only the air from the east source region encountered cloud and precipitation formation and may have undergone aerosol scavenging. Eastern Colorado was found to have a

population density of 55.6 persons per square mile; the largest of the three source regions (Table 2). Thus, these large CN concentrations most likely came from the Denver metro area where the air parcel traveled around in route to SPL (Fig. 5). This finding is consistent with the results of an investigation into pollution sources by Borys, et al. (1986). They found that easterly airflow could bring air to SPL from local and distant sources in the east.

The north to northwest source region had a significantly lower source strength and yet the second largest CN values. Lowenthal, et al. (2001) found that CN concentrations under N-NW winds were slightly higher than under S-SW winds and attributed these differences to stronger surface emissions from the adjacent Yampa valley and beyond to the west.

The largest SO_2 and NO_2 concentrations came from the west to southwest source region and the lowest values came from the east source region even though the east region had the largest population density. Given that the air arriving from the east encountered precipitation, a probable cause for the low values would be gas scavenging by cloud and precipitation. But, in the air arriving from the east, the large CN concentrations did not correspond to large SO_2 and NO_2 concentrations. In fact, the east region had the lowest SO_2 and NO_2 concentrations.

So, why did the largest CN concentrations and the smallest SO_2 and NO_2 concentrations come from the east source region? With the highest population density, one would expect the region to have the largest emissions of CN, SO_2 and NO_2. If so, it may have been that the CN were scavenging less effectively than the SO_2 and NO_2 by cloud and precipitation formation.

We, now, estimate the scavenging efficiencies for CN, SO_2 and NO_2.

Lowenthal, et al. (2001) measured the scavenging of CN with diameters greater than 0.0087 μm by wintertime precipitating clouds that enveloped SPL. From their average February 2001 data, we estimate, on average, that 50% of these particles were scavenged. Also, we estimated the scavenging of ultrafine CN and CN from a cloud event at SPL on 9 January 2002 (Fig. 7). During the cloud formation, the ultrafine CN decreased 58% (12,000 to 7,000 cm^{-3}) and the CN decreased 50% (7,000 to 3500 cm^{-3}). Our results are consistent with those of Lowenthal at al. and with those summarized by Pruppacher and Klett (1998). Thus, about 50% of the CN are removed during cloud formation at SPL.

We estimated SO_2 and NO_2 scavenging from measurements at SPL when a cloud formed between measurement periods. The difference between the pre-cloud and in-cloud values was determined. If there was a decrease after cloud formation, then scavenging was assumed to have occurred. The results of the scavenging analyses are given in Table 3. It can be seen in the table, the SO_2 values show no consistent scavenging perhaps due to concentrations often below the 1 ppb threshold of the measurement technique. The NO_2 values show consistent scavenging with a range from 20% to 63%. Thus, the NO_2 measurements showed scavenging during cloud formation comparable to that of that CN; around 50%.

The air that traveled from the high population-density east source region to SPL had the concentrations of CN, SO_2 and NO_2 reduced by cloud and precipitation scavenging. In contrast, the air that traveled from the lower population-density west to southwest source region had higher concentrations of SO_2 and NO_2 most likely because no precipitation scavenging was encountered. However, the CN concentrations from the east source region were higher than those from the west to southwest region. Why? Were the CN scavenged less efficiently than SO_2 and NO_2 by cloud and precipitation formation? Not so based on our SPL scavenging analysis. Thus, during this east-wind event, it appears the CN emissions were larger than the SO_2 and NO_2 emissions in east source region and just the opposite for the west to southwest source region.

7. CONCLUSIONS

This investigation provides insights into air parcel source regions, source strengths and pollutant transport at SPL. We show that air parcels arriving at SPL during the January 2001 east-wind event originated from three distinct source regions (west to southwest, east, north to northwest), traveled long and short distances and carried pollutants across those distances. The east source region produced the highest CN concentrations, most likely from the Denver metro area, even though the parcels traveled through clouds and precipitation. Parcels from the other regions encountered no precipitation. Surprisingly, the largest CN and smallest SO_2, NO_2 concentrations came from the east region. We were unable to explain this finding by more efficient removal of SO_2, NO_2 than CN by cloud a precipitation formation. It appears the CN emissions were larger than the SO_2 and NO_2 emissions in the east source region and just the opposite in the west to southwest source region..

8. ACKNOWLEDGEMENTS

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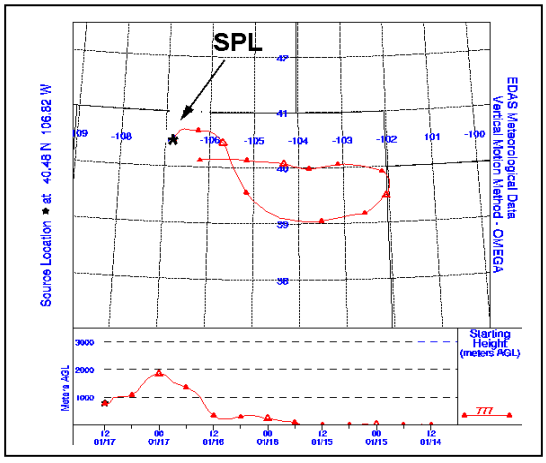


Figure 1. The horizontal and vertical trajectories of an air parcel arriving at SPL at 0500 MST (12Z), 17 January 2001 after traveling for 72 hours.

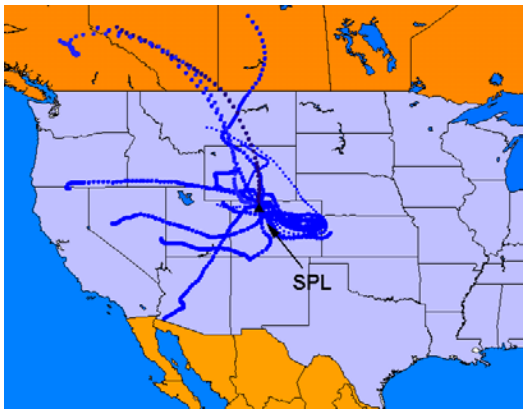


Figure 2. 72-hour back trajectories for air arriving at SPL between 0900 MST, 15 January and 1300 MST, 18 January.

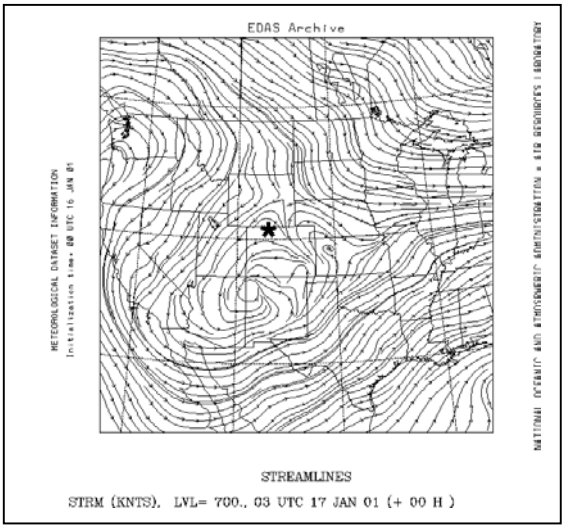


Figure 3a. Streamlines showing a "snapshot" of the air moving at 700 mb at 2000 MST (03Z), 17 January 2001. The location of SPL is noted with *.

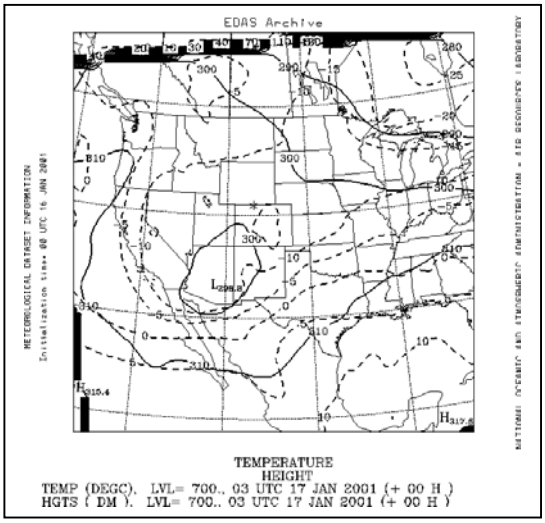


Figure 3b. Height of the 700 mb pressure surface above sea level in decameters (310 dm = 3100m) at 2000MST (03Z), 17 January 2001. SPL is noted with *.

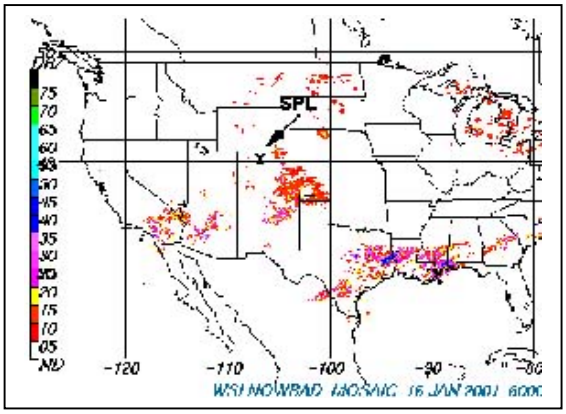


Figure 4. Radar image showing locations of precipitation at 2300MST, 15 January 2001 (0600Z, 16 January).

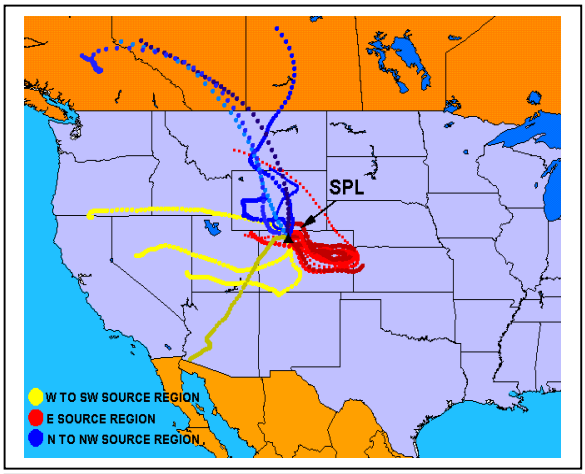


Figure 5. Trajectory analysis revealed three source regions for air arriving at SPL: west to southwest (yellow), east (red) and north to northwest (blue).

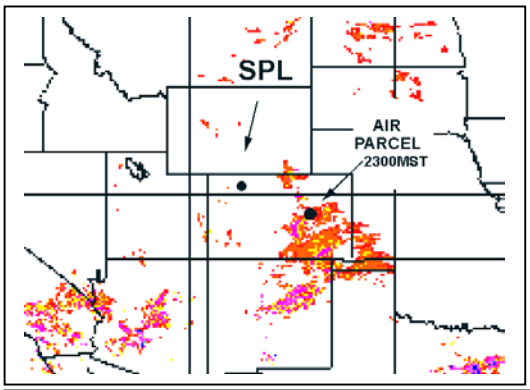
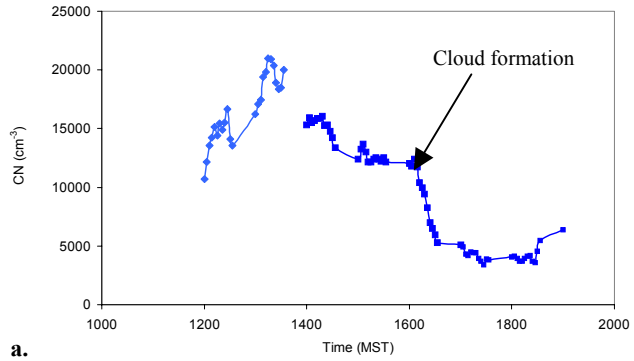


Figure 6. Approximate location of air parcel at 2300MST, 15 January 2001,shown superimposed on radar image.

TABLE 2

Comparison of population densities of the three source regions

Region	Population	Area (mile^2)	Pop/ mile^2
E	3,898,044	70,165	55.56
W-SW	9,765,275	339,158	34.25
N-NW	1,395,977	242,652	5.65



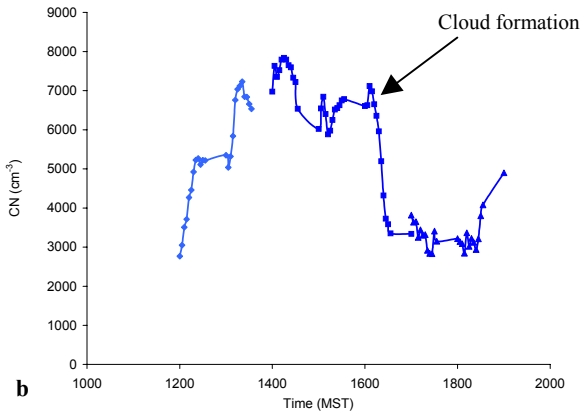


Figure 7. Ultrafine CN concentratons (a) and CN concentrations (b) during a cloud-formation event at SPL on 9 January 2002. Cloud formation began at 1600 MST as indicated by the precipitous decline in concentrations.

TABLE 1

SPL Source Region Comparison of Average Gas And CN concentrations

	Source Region		
	W-SW	E	N-NW
SO_2(ppm)	**0.0043**	0.00084	0.0014
stderror	0.0015	0.00030	0.0004
NO_2(ppm)	**0.0014**	0.00030	0.00022
stderror	0.0013	0.00010	0.00004
O_3(ppm)	0.0254	0.0241	0.0271
stderror	0.00011	0.00009	0.00005
CN(cm^{-3})	1477.36	**2356.14**	1909.70
stderror	156.15	289.25	295.19

TABLE 3

SO_2 and NO_2 measurements during cloud formation at SPL

SPL in cloud?	Date	Time (MST)	SO_2 (ppm)	NO_2 (ppm)
No	17 Jan 2000	1700	0.000	0.000024
Yes	17 Jan 2000	2100	0.0034	0.000018
Percent change			100% increase	25% decrease
No	21 Jan 2000	0500	0.0075	0.000073
Yes	21 Jan 2000	0900	0.0057	0.000029
Percent change			24% decrease	60% decrease
No	20 Jan 2001	0100	0.0035	0.00015
Yes	20 Jan 2001	0500	0.000	0.000057
Percent change			100% decrease	62% decrease
No	6 Jan 2002	0800	0.000	0.00086
Yes	6 Jan 2002	1100	0.0048	0.00069
Percent change			100% increase	20% decrease
No	9 Jan 2002	1400	0.000	0.0074
Yes	9 Jan 2002	1700	0.0018	0.0057
Percent change			100% increase	23% decrease