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Long-range transport of Asian dust to the Lower Fraser Valley, British Columbia, Canada

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Abstract. For the first time, long-range transport of "Kosa" mineral aerosol from western China to southwestern British Columbia is documented. This late April 1998 event coincided with an episode of photochemical smog and reduced dispersion in the Lower Fraser Valley (LFV). Filter samples in the region show a massive injection of crustal elements (Si, Fe, Al, and Ca) with concentrations of Si approximately double those previously recorded. Ratios of these elements to Fe are shown to be statistically similar to ratios observed in mineral aerosol events in Hawaii and China. On the basis of the difference between observed and expected elemental concentrations and reconstructed soil mass in the episode, it is estimated that Asian dust contributed 38–55% to observed PM_{10} in the LFV, the remainder being attributed to local sources. Comparison of the April 1998 event with two spring meteorological analogs is consistent with this estimate. Mesoscale model simulations suggest that mineral dust was incorporated into the planetary boundary layer as a result of strong subsidence over the interior of southern British Columbia and Washington State which permitted interception of lower tropospheric elevated aerosol layers by surface-based mixing processes over mountainous terrain. Surface easterly ("outflow") winds then transported this material into the Lower Fraser Valley where it contributed significantly to total particulate loadings and an intense haze. This mechanism is consistent with the observed spatial and temporal distribution of PM_{10}.

1. Introduction

Long-range transport of both mineral dust and anthropogenic pollutants from the major continents has been the subject of intense investigation due to the potential impact of such pollutants on the global radiative budget and atmospheric chemistry [*Sokolik et al*., this issue]. Recent studies include the North Atlantic Regional Experiment (NARE) [*Daum et al*., 1996] and investigations of transport from Africa [e.g., *Jonquieres et al*., 1998; *Tyson et al*., 1998].

Intense frontal activity in western China, mostly during spring, provides a mechanism for injection of surficial material into the lower and middle troposphere [*Merrill et al*., 1989]. Rapid, eastward long-range transport (LRT) of this mineral aerosol (often referred to as Kosa or yellow dust) to the North Pacific has been well documented [*Merrill et al*., 1989; *Xiao et al*., 1997] and may contribute to disruption of aircraft operations, visibility impairment at locations as far afield as Hawaii [*Merrill et al*., 1989], eolian transport of anthropogenic material [*Nishikawa et al*., 1991], and oceanic enrichment of iron. It may also have a significant impact on tropospheric chemistry and radiative properties. Previous analyses of Kosa aerosol suggest that it is rich in soil-derived elements silicon (Si), calcium (Ca), aluminum (Al), and iron (Fe). Until April 1998, there had been no direct evidence of significant LRT of Asian dust to the North American continent. However, *Jaffe et al*. [1999] and *Berntsen et al*. [1999] recently provided the first documentation of springtime transport of anthropogenic pollutants from East Asia to northwestern Washington State. Their results show that surface emissions over East Asia may be transported to North America in ~6 days.

In late April and early May 1998, western North America, including much of southern British Columbia, experienced elevated PM_{10} concentrations and an intense haze. This event was widely reported in the popular media and generally attributed in the United States to transport across the North Pacific of crustal material from an intense dust storm in western China on April 18–19, 1998. Supporting data (including aircraft, lidar, surface and satellite observations), tracing the transport of dust across the North Pacific from Asia with arrival over the western United States and southern British Columbia as early as April 25, can be found elsewhere in this issue [*Husar et al*., this issue; *Tratt et al*., this issue].

Arrival of tropospheric Asian dust over western North America in late April 1998 coincided with unusually warm, anticyclonic springtime weather in the Lower Fraser Valley (LFV) of southwestern British Columbia. Not surprisingly, this unusual combination of events raised important questions regarding (1) the extent to which elevated PM_{10} concentrations observed in the LFV during this event could be attributed to

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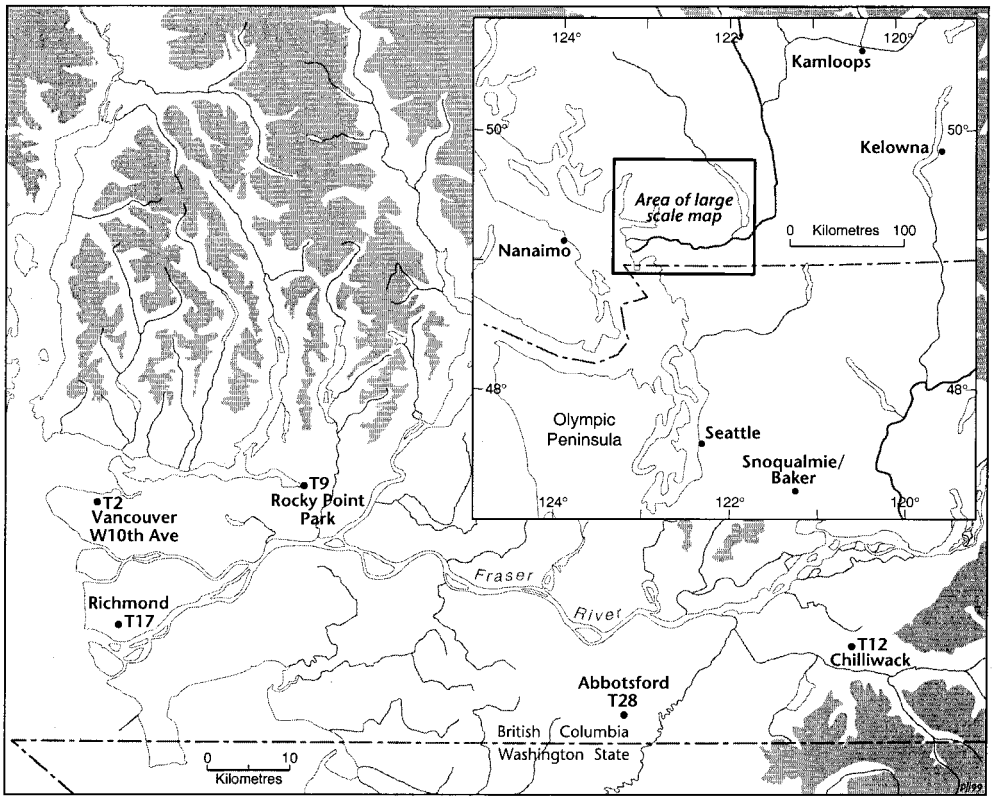

Figure 1. Map of the Lower Fraser Valley and wider region showing places mentioned in the text.

local meteorology and local emissions rather than nonlocal sources (e.g., forest fires or Asian dust) and (2) meteorological mechanisms by which lower tropospheric dust could be mixed into the planetary boundary layer (PBL) over the LFV.

In this study the elevated PM_{10} event of April–May 1998 in the LFV is examined in detail in order to establish the contribution of LRT from Asia. Evidence is drawn from spatial and temporal patterns of PM_{10} in the LFV, chemical analyses of filter samples at the peak of the event, and from comparison with other spring pollutant episodes. Finally, numerical model simulations are used to trace the transport of dust across the region and illustrate mechanisms by which Asian dust may be mixed into the PBL and transported to the LFV.

2. Air Pollution Meteorology of LFV

The LFV (Figure 1) has a rapidly growing population of 2.0 million mostly located in Greater Vancouver at the northwestern edge of the valley. Eastward, the valley becomes increasingly rural although several urban centers exist (most notably, Abbotsford and Chilliwack). The valley floor is nearly flat, at an elevation of no more than a few hundred meters above sea level, while valley walls to the north rise to 2000 m above sea level within 10 km of the floor. Despite its west coast midlatitude setting, winds in the LFV are predominately easterly throughout the year due to channeling of synoptic scale southwesterly winds by regional topography. However, during summer, daytime sea breezes result in increased frequency of westerly, up-valley flow [*Steyn and McKendry*, 1988] which may transport urban pollutants throughout the LFV and its tributaries [*McKendry et al*., 1998]. The region occasionally experiences conditions of degraded air quality in summertime, largely as a result of exceedances of the National Ambient Air Quality Objective for ozone (82 ppb, 1 hour average maximum acceptable level) and degraded visibility [*Steyn et al*., 1997]. Episodes of photochemical air pollution (including poor visibility) generally occur during summertime anticyclonic conditions [*McKendry*, 1994; *Pryor et al*., 1994b] when local thermotopographic circulations and reduced mixing depths strongly influence the transport and dispersion of pollutants [*Steyn and McKendry*, 1988].

While the meteorology, chemistry, and distribution of photochemical pollution in the LFV are reasonably well known, particulate pollution in the region is poorly understood. *McKendry* [1999] shows that PM_{10} concentrations in the LFV are relatively low when compared to larger urban regions such as the Los Angeles basin, other Canadian centers, Philadelphia, Birmingham (England) or a range of urban or rural sites across Europe. Mean concentrations are very similar to those observed in unpolluted rural sites on the Swiss plateau or in Scandinavia.

Other recent studies have focused on the nature of visibility degrading fine aerosols in the LFV [*Pryor et al*., 1994a, 1997] and analysis of particulate measurements at two Vancouver sites [*Brook et al*., 1997]. Primary emissions of PM_{10} in the LFV are dominated by transportation sources (including road dust). Because of its isolated west coast setting and predominantly easterly surface winds, the LFV is seldom influenced by long-range transport (LRT) of particulate matter. Most sources of particulate matter lie in the Canadian portion of the LFV, although point sources have been identified across the border in the United States [*Hoff et al*., 1997].

3. Data and Model

Numerous pollutant species are monitored continuously throughout the LFV by the Greater Vancouver Regional District (GVRD) using standard quality assurance and quality control procedures. In addition, meteorological measurements (principally wind speed, wind direction, temperature, and humidity) are made at several sites. Hourly PM_{10} is measured in the LFV using the tapered element oscillating microbalance (TEOM) instrument. In the LFV monitoring network the TEOM sample chamber and inlet air are heated to 40°C (rather than the usual 50°C) to minimize volatilization effects [*Mignacca and Stubbs*, 1999].

Two data sets permit analysis of the chemical composition of particulate matter during the April 1998 event. Firstly, modular aerosol monitoring samplers are operated as part of the Interagency Monitoring of Protected Visual Environments (IMPROVE) program throughout the United States. Snoqualmie/Baker and Puget Sound/Seattle (Figure 1) are the two closest IMPROVE monitoring locations to the LFV. These sites have been operational since 1993 and 1996, respectively. A full site consists of four modules each designed for analysis of different types of particulate matter [*Malm et al*., 1994]. Three modules measure 24 hour average $PM_{2.5}$, while the fourth module measures PM_{10}. Samples are taken on a twice-weekly schedule and are analyzed for various chemical constituents, including a suite of elements, organic and elemental carbon, and some ions. Secondly, at Rocky Point Park (RPP) and Vancouver West 10th Avenue in the LFV (Figure 1), dichotomous samplers are operated routinely as part of the Canadian National Air Pollution Surveillance (NAPS) network. These provide 24 hour average filter samples of $PM_{2.5}$ and $PM_{2.5-10}$ on a 6 day sampling schedule. All dichotomous filters are analyzed for 50 chemical species by nondestructive X-ray fluorescence (Kevex 770/8000 energy dispersive X-ray fluorescence (EDXRF) spectrometer). After EDXRF analysis each filter is further analyzed by ion chromatography. Sampling and analytical methods are described in further detail by *Brook et al*. [1997].

Meteorological transport processes associated with the April 1998 event were examined with the Canadian MC2 atmospheric model. In this model [*Benoit et al*., 1997], advection is semi-Lagrangian with a semi-implicit time step. This facilitates straightforward tracking of atmospheric tracers. The Recherche en Prévision Numérique full-physics package is used, which is similar to that used with the Canadian Meteorological Centre (CMC) suite of operational models. The force-restore method [*Deardorff*, 1978] describes surface exchanges, and a 1.5 order turbulent-kinetic energy predictive equation [*Benoit et al*., 1989] parameterizes vertical turbulent diffusion. Surface forecasts are specified at shelter height (2 m) and anemometer height (10 m) using a surface layer model based on similarity theory. MC2 uses a one-way (cascade) nesting strategy, where a coarse-grid forecast provides initial and boundary conditions for a fine-grid forecast, and there is no upscale feedback. A 90 km grid simulation is initialized at 0000 UTC, a 30 km grid is initialized at 0600 UTC, and a 10 km grid is initialized at 1200 UTC. The 6 hour time increment is chosen to allow inertial-gravity waves to disperse from the coarser grid before it is used to initialize the finer grid. This is also the next synoptic time, and a new surface analysis is available to update the model fields.

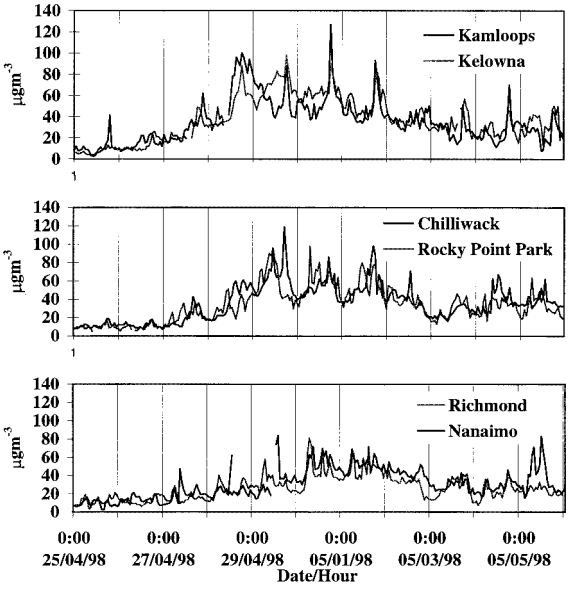

Figure 2. Time series of hourly PM_{10} concentrations for stations plotted east (top) to west (bottom) for the period 0000 Pacific standard time (PST), April 25, to 0000 PST, May 5, 1998 (dates are dd/mm/yy).

4. Results

4.1. Background and Regional Context

Elevated particulate concentrations in the LFV during late April 1998 coincided with high concentrations observed across much of southwestern British Columbia and the western United States [*Husar et al*., this issue]. Time series of PM_{10} concentrations across southwestern British Columbia plotted from west to east are shown in Figure 2. At Kamloops in the east (shown in Figure 1) hourly concentrations increased steeply on April 28 to ~100 $\mu g\ m^{-3}$. These were the highest sustained concentrations at this location during the entire event. On April 28, concentrations also were observed to increase at Kelowna and Chilliwack but did not peak until the following day. In the western portion of the LFV and on Vancouver Island (Richmond and Nanaimo) peak concentrations occurred later (April 30) and were of lower magnitude than concentrations observed at sites further east.

Serendipitous aircraft observations of the Asian dust plume over western Washington state, together with size segregated surface dust samples, indicate a peak in the volume distribution function in the 2–4 μm range with 30–50% of the PM_{10} mass less than 2.5 μm [*Husar et al*. this issue]. Between April 28 and May 1, 1998, average $PM_{2.5}/PM_{10}$ ratios in southwestern British Columbia were consistent with these observations: Kamloops (0.47 ± 0.15), Kelowna (0.45 ± 0.12), Chilliwack (0.53 ± 0.07) and Nanaimo (0.42 ± 0.10). These values are somewhat lower than average ratios at Vancouver and Victoria of 0.57–0.60 [*Dann*, 1994]. Consequently, although $PM_{2.5}/PM_{10}$ ratios at all sites in the region were consistent with a LRT crustal signature during the April 1998 event, they were not markedly lower than typical ratios.

4.2. Comparison of 1998 Event With Spring Meteorological Analogs

Photochemical smog episodes during spring are uncommon in the LFV. This raises the possibility that high PM_{10} concen-

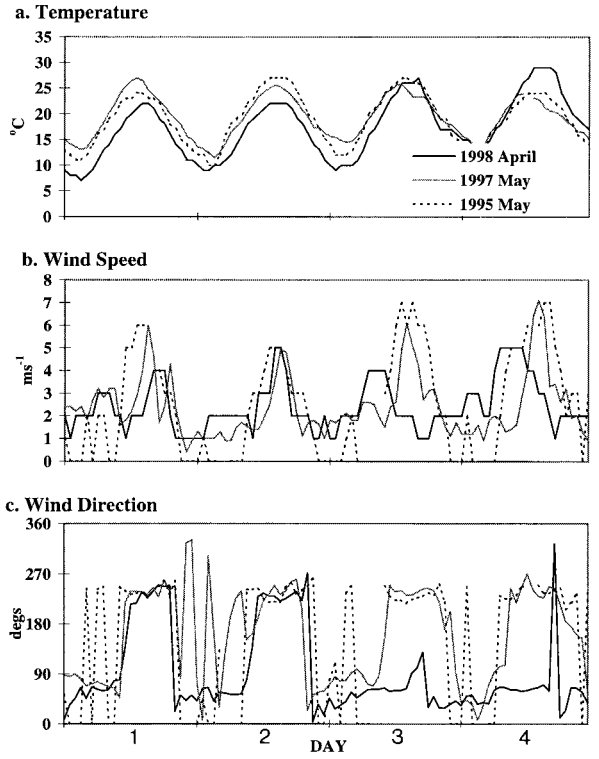

Figure 3. Four day times series of (a) temperature (b) wind speed, and (c) wind direction at Chilliwack for April 27–30, 1998, and meteorological analogs May 27–30, 1995 and May 12–15, 1997.

trations observed in the valley during April 1998 were associated with sources or processes specific to spring which are not present during summer events (e.g., biogenic emissions or spring ploughing). To investigate this possibility, spring analogs were sought in which photochemical activity and dispersion conditions were of similar magnitude to those observed in the April 1998 event. Two cases were identified (May 27–30, 1995 and May 12–15, 1997) when synoptic conditions, O_3 concentrations, temperatures, and wind speeds in the LFV were comparable to the unusual conditions observed during late April 1998.

April 29, 1998, and the two analogs were similar with respect to 500 hPa circulation patterns. In each case, midtropospheric flow was southwesterly and associated with a ridge of high pressure over the region. For the two analogs the ridge was centered to the east of the LFV, while for April 29, 1998, it was aligned along the British Columbia coast. Surface pressure patterns all showed weak gradients. On May 29, 1995, a surface ridge penetrating northward from the southwest extended a weak northerly flow over the LFV, while May 14, 1997, was characterized by a slack surface pressure gradient. On April 29, 1998, a thermal trough extending from the south and a weak high pressure to the north produced offshore winds (i.e., "outflow") across southwestern British Columbia.

Time series of meteorological variables are shown in Figure 3. For each event, maximum hourly temperatures at Chilliwack exceeded 26°C by the third day of the event (Figure 3a) and were associated with moderate wind speeds of 4–7 m s^{-1} (Figure 3b). At Chilliwack, highest wind speeds were associated with daytime westerlies during the May 1995 and 1997 events. In contrast, at the peak of the April 1998 event, light easterly "outflow" winds predominated at Chilliwack. This weak surface wind stress probably precludes entrainment of local surficial materials as an explanation for the high particulate matter concentrations observed during April 1998.

Variations in pollutant concentrations for each event are compared in Figures 4a–4e. At both Chilliwack and Abbotsford (Figures 4a, 4b), PM_{10} concentrations increased markedly during daytime on both April 29 and 30, 1998 (days 3 and 4 in Figure 4). At Chilliwack, peak daily PM_{10} concentrations reached 63 $\mu g\ m^{-3}$ on April 29, approximately double the maximum daily concentrations observed during the 1995 (32 $\mu g\ m^{-3}$) and 1997 (39 $\mu g\ m^{-3}$) analogs. In contrast to the two analogs a strong diurnal variation in PM_{10} also occurred at these sites on April 29 and 30, 1998. It is possible that this overnight decrease in PM_{10} concentrations was associated with the marked decrease in easterly (outflow) wind speeds over-

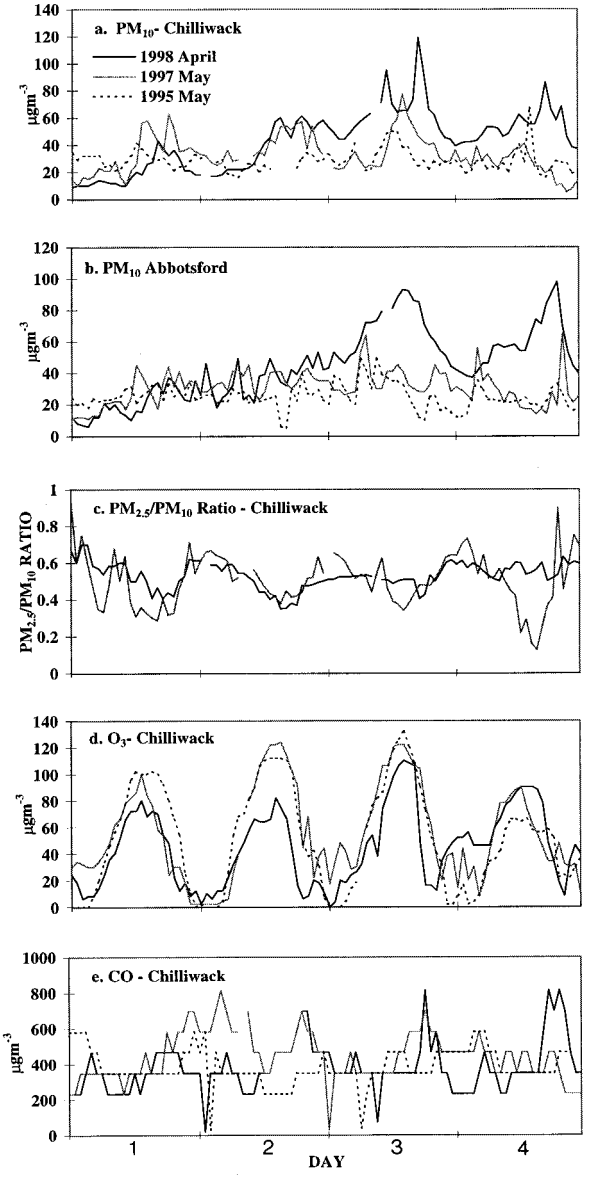

Figure 4. Four day times series of (a) PM_{10} at Chilliwack, (b) PM_{10} at Abbotsford, (c) $PM_{2.5}/PM_{10}$ ratios, (d) O_3, and (e) CO concentrations at Chilliwack for April 27–30, 1998, and meteorological analogs May 27–30, 1995 and May 12–15, 1997.

night (Figure 3b). $PM_{2.5}/PM_{10}$ ratios at Chilliwack (Figure 4c) show similar temporal patterns and magnitudes for the 1997 and 1998 events ($PM_{2.5}$ data were not available for 1995). This is not surprising given the similarity between mean ratios in the region and those expected to occur with LRT of Asian dust (see earlier discussion). If unusually high concentrations of PM_{10} in late April 1998 were associated with local anthropogenic sources (i.e., transportation sources), it might be expected that O_3 and CO concentrations (Figures 4d, 4e) would show increases proportionate to those observed for PM_{10}. However, O_3 and CO concentrations were of similar magnitude for each of the three episodes and indicate that anthropogenic emissions, dispersion conditions, and photochemistry were probably comparable in each case. This leaves either a local crustal source (e.g., spring ploughing) or an alternative nonlocal source as being responsible for a significant portion of the elevated concentrations observed in the LFV in late April 1998. The regional nature of the elevated PM_{10} concentrations, the relatively light winds and the fact that spring analogs did not show similar concentrations all suggest that a local crustal source was unlikely. Further evidence is provided by an examination of the elemental composition of particulate matter.

4.3. Elemental Composition

Previous investigations of the composition of transported Asian dust show it to be enriched in crustal elements Si, Al, Fe, Ca, K, and Ti. Most importantly, ratios of these elements appear to be consistent from dust storm to dust storm and appear to be reasonably independent of transport distance and particle size range [*Braaten and Cahill*, 1986; *Nishikawa et al*., 1991]. Analyses of the elemental composition of particulate matter in the western Washington/southwestern British Columbia region therefore provide the best opportunity to identify the "signature" of Asian dust and to assess its relative contribution to the high concentrations of particulate matter observed in the LFV in late April 1998.

Fortunately, the peak of the April 1998 event coincided with regular ($PM_{2.5}$) sampling at the two closest IMPROVE sites at Snoqualmie/Baker and Puget Sound, Seattle (Figure 1). At these sites, $PM_{2.5}$ concentrations were 24.3 and 16.7 $\mu g\ m^{-3}$, respectively, on April 29, 1998, and were overwhelmingly dominated by elements associated with a crustal source (notably, Si, Al, and Fe). For example, at Snoqualmie/Baker, concentrations of Si (Figure 5a) far exceeded concentrations observed in the previous five years, while the percentage of $PM_{2.5}$ mass attributed to soil (reconstructed soil mass is based on 2.20Al + 2.49Si + 1.63Ca + 2.42Fe + 1.94Ti [*Malm et al*., 1994]) was ~60%, more than twice the highest proportions observed in the historic record (Figure 5b). These observations are consistent with those observed at other IMPROVE sites throughout western North America [*Husar et al*., this issue].

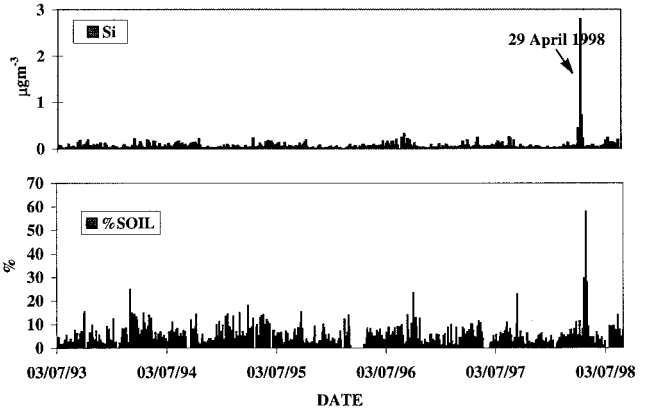

Figure 5. Twice-weekly daily silicon concentrations and reconstructed soil mass for the Snoqualmie/Baker IMPROVE site for July 3, 1993 to August 29, 1998 (dates are dd/mm/yy). The peak daily value for each series is for April 29, 1998.

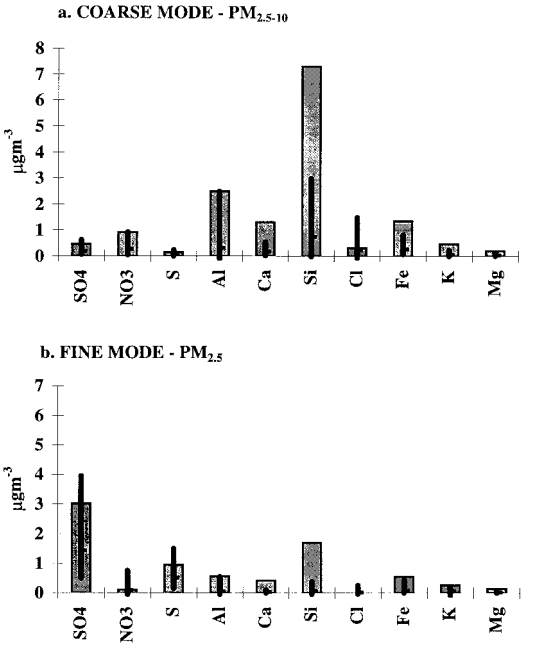

Figure 6. Concentrations for April 29, 1998 (solid bars) at Rocky Point Park, Vancouver, for selected ions and elements compared to historical (1996–1998) 99th percentiles (extent of top whisker), means (horizontal bar), and standard deviations (extent of bottom whisker) for (a) coarse mode particles ($PM_{2.5–10}$) and (b) fine mode particles ($PM_{2.5}$).

A similar pattern is evident in the elemental composition of both fine ($PM_{2.5}$) and coarse ($PM_{2.5–10}$) mode particulate matter collected at RPP on April 29, 1998, and at West 10th Avenue (See Figure 1). As both sites show similar patterns, results from RPP only are presented below. In Figure 6, concentrations of major elements and ions (solid bars) on April 29 are compared to mean values, 99th percentiles, and standard deviations for the period 1996–1998. The extent to which the major crustal elements (Ca, Si, and Fe) on April 29, 1998, exceed the 99th percentiles is striking. For the coarse mode, observed Si concentrations were more than twice the 99th percentile and almost double the previous highest concentration in the record. Other elements and ions (e.g., SO_4, NO_3, and S) were within the range of historic concentrations. These results confirm that on April 29, 1998, both the IMPROVE sites of northern Washington State and the NAPS sites in the LFV experienced a remarkable crustal particulate matter event.

During winter in the eastern LFV, strong outflow winds occasionally give rise to intense local crustal events during which PM_{10} concentrations of ~100 $\mu g\ m^{-3}$ may be sustained for several days [*McKendry*, 1999]. Such events provide a useful indication of the local crustal signature. A particularly intense episode occurred between December 31, 1994 and January 7,

Table 1. Fine Mode Elemental Ratios at Rocky Point Park (RPP), LFV, Compared to Ratios Observed During Kosa Events at Beijing, China, and Mauna Loa, Hawaii, and During a Local Crustal Event in the LFV

	Beijing[a] (B)	Hawaii[b]	Chilliwack IMPROVE[c] Mean ± s.d.	RPP April 29, 1998	1994–1995 Crustal Event[d]
Size, μg m^{-3}	2–4.0	0.5–3.0	0–2.5	0–2.5	0–2.5
Si/Al	3.37	2.67	1.88 ± 0.47	3.04	2.91
K/Al	0.31	0.44	1.45 ± 0.97	0.47	0.52
Ca/Al	0.77	0.96	0.58 ± 0.23	0.76	0.23
Ti/Al	0.06	0.07	0.08 ± 0.05	0.09	0.06
			χ^2 *Test (versus B)*		
Probability	···	0.97	0.17	0.99	0.90
χ^2	···	0.25	4.90	0.13	0.58

Chi-squared significance tests of elemental ratios observed at Beijing with ratios at other sites are also shown.
[a]Elemental ratios sampled at Beijing during dust storm [*Braaten and Cahill*, 1986].
[b]Mean elemental ratios sampled at Mauna Loa, Hawaii, during dust events [*Bratten and Cahill*, 1986].
[c]Mean and standard deviation of elemental ratios 1994–1995 (113 days) from IMPROVE site.
[d]Mean of three sampling days December 31, 1994 to January 7, 1995.

1995, and coincided with a short period (~1 year) of IMPROVE, monitoring at Chilliwack in the eastern LFV. Ratios of fine mode crustal elements to Al during this known crustal episode (note that Fe was not monitored at Chilliwack) are shown in Table 1 and statistically compared with the April 1998 event and Kosa aerosol signatures observed in China and Hawaii. Although the 1994–1995 LFV crustal event shows some similarities to the Kosa elemental signature (i.e., high Si/Al ratios), it suggests that the high proportions of Ca typical of crustal material from the alkaline semi-arid regions of China are not apparent in local crustal events. Furthermore, the 1994–1995 crustal episode demonstrates that even with strong winds (gusting to 14 m s^{-1}) and PM_{10} concentrations in excess of those observed during April 29, 1998, locally generated fine mass ($PM_{2.5}$) was still considerably less than that observed during the April 1998 event. $PM_{2.5}/PM_{10}$ ratios were ~0.2, while fine mode Si concentration reached only 0.9 μg m^{-3} in this winter event compared to 1.71 μg m^{-3} at RPP on April 29, 1998. Under the light wind conditions of April 29, 1998, it is therefore unlikely that high observed concentrations of crustal material were of local origin.

In Table 2, ratios of fine mode crustal elements (this time to Fe) observed on April 29, 1998, in the western LFV and western Washington State are further compared with observations from Hawaii and Beijing [*Braaten and Cahill*, 1986] and to ratios observed during meteorological analogs in the LFV. Chi-square tests are used to assess the significance of the comparisons. Elemental ratios at both Snoqualmie/Baker and RPP on April 29 are remarkably similar to those observed during multiple episodes of LRT of Kosa dust to Hawaii and also to ratios observed in Beijing during a dust storm. This is strongly supported by chi-square tests (probabilities and χ^2 statistics are shown in Table 2). Mean ratios at RPP and those associated with the two spring analog events show quite different signatures characterized by much lower Si, Ca, and Al ratios. Finally, the April 1998 crustal signature is statistically different from that of an intense midsummer photochemical smog episode (July 28, 1998) during which PM_{10} concentra-

Table 2. Fine Mode Elemental Ratios at Rocky Point Park, LFV, and at Snoqualmie/Baker, Washington, for April 29, 1998, Compared to Mean Values/Analogs at Rocky Point Park (RPP) and Ratios Observed During Kosa Events Observed at Beijing, China, and Mauna Loa, Hawaii

	Comparative Elemental Ratios						April 29, 1998	
	Beijing[a] (B)	Hawaii[b]	RPP[c] Mean	RPP May 27, 1995	RPP May 16, 1997	RPP July 28, 1998	RPP	SNOQ/B[d]
Size, μg m^{-3}	2–4.0	0.5–3.0	0–2.5	0–2.5	0–2.5	0–2.5	0–2.5	0–2.5
Si/Fe	3.5	3.4	0.94	2.71	1.3	1.64	3.11	3.06
K/Fe	0.32	0.56	0.70	0.69	0.41	0.48	0.48	0.51
Ca/Fe	0.80	1.22	0.37	0.36	0.52	0.45	0.78	0.71
Ti/Fe	0.06	0.09	0.06	0.05	0.0	0.0	0.09	0.08
Al/Fe	1.04	1.27	0.42	1.39	0.21	0.27	1.02	1.87
				χ^2 *Test (Versus B)*				
Probability	···	0.98	0.57	0.91	0.63	0.76	1.00	0.93
χ^2	···	0.47	2.92	0.97	2.57	1.85	0.14	0.85

Chi-square significance tests of elemental ratios observed at Beijing with ratios at other sites are also shown.
[a]Elemental ratios sampled at Beijing during dust storm [*Braaten and Cahill*, 1986].
[b]Mean elemental ratios sampled at Mauna Loa, Hawaii, during dust events [*Braaten and Cahill*, 1986].
[c]Mean elemental ratios at Rocky Point Park, 1996–1998.
[d]Elemental rations at Snoqualmie/Baker IMPROVE site, Washington, United States.

Table 3. Estimated Contribution of Kosa Aerosol to the April 29, 1998, Episode (All Values in $\mu g\ m^{-3}$)

	April 29, 1998		99 Percentiles[b]		July 28, 1998		April 29—99 Percentile (Difference)		April 29 to July 28 (Difference)	
Element	C	F	C	F	C	F	C	F	C	F
Si	7.31	1.71	2.98	0.38	2.50	0.18	4.33	1.33	4.81	1.53
Al	2.50	0.56	2.50	0.54	0.78	0.03	0.00	0.02	1.72	0.53
Fe	1.35	0.55	0.81	0.44	0.55	0.11	0.54	0.11	0.80	0.44
Ca	1.31	0.42	0.54	0.10	0.46	0.05	0.77	0.32	0.85	0.37
Ti	0.12	0.05	0.07	0.02	0.05	0.00	0.05	0.03	0.07	0.05
Total Crustal (C + F)	15.89		8.38		4.71		7.50		11.17	
PM_{10}	47.46		38		42		...		...	
RSM[a]	36.94		19.3		10.9		18 (38%)[c]		26 (55%)[c]	

Coarse (C) and fine (F) mode concentrations are compared with 99th percentiles and values for an intense photochemical episode on July 28, 1998.

[a]Reconstructed soil mass.

[b]Based on data 1994–1998 ($N = 248$).

[c]% of April 29, 1998, PM_{10}.

tions reached levels comparable to those observed on April 29, 1998. This evidence, together with that presented in Table 1, supports the hypothesis that during April 1998 the LFV was influenced by crustal material of Asian origin.

To estimate the proportion of PM_{10} on April 29, 1998, which could be reasonably attributed to Kosa dust, elemental concentrations on April 29, 1998, were subtracted from both 99th percentiles and July 28, 1998 values (Table 3). Given that the 99th percentile of PM_{10} in the LFV is associated with local winter crustal events, this concentration probably represents a conservative estimate of expected local crustal contribution to PM_{10} on April 29, 1998. Elemental concentrations for the intense photochemical episode on July 28, 1998, during which PM_{10} concentrations were of similar magnitude to April 29, 1998, provide a second estimate of expected local contributions to PM_{10}. Concentrations of the suite of crustal elements on April 29, 1998, exceeded their 99th percentiles in total by 7.5 $\mu g\ m^{-3}$ (16% of total PM_{10} on April 29) and exceeded July 28, 1998, values by 11.2 $\mu g\ m^{-3}$ (24% of total PM_{10} on April 29). These values represent lower limits to the estimated contribution of Kosa dust on April 29, 1998. Each crustal element would be expected to be associated with their normal oxides and due to their molecular form would contribute a greater proportion to the total PM_{10} mass than indicated by the pure elements alone. By reconstructing soil mass to account for the additional material associated with the elements in their oxidized form [*Malm et al*., 1994] (see above) a more reasonable estimate of the Kosa input can be attained. Using this approach, concentrations of Si, Al, Fe, Ca, and Ti exceeded their 99th percentiles by a total of 18 $\mu g\ m^{-3}$ and July 28, 1998, values by 26 $\mu g\ m^{-3}$. On this basis, Kosa contribution to total PM_{10} concentration at RPP is estimated to be 38–55%.

In reconstructing soil mass it is assumed that the approach developed by *Malm et al*. [1994] is applicable to Kosa aerosol and across the full range of particle sizes. Unfortunately, with the limited range of species/elements available from NAPS analyses, an average of 45% of total reconstructed mass remains unexplained and is most likely associated with carbonaceous species [*Brook et al*., 1997]. Without a full reconstruction of total mass from the speciated data it is therefore not possible to assess the accuracy of the soil reconstruction and the estimates of mineral aerosol contribution to the April 29 event so derived. However, this estimate is consistent with the observation that concentrations during the April 1998 event were approximately double those in the two spring analogs.

4.4. Meteorological Transport Processes

To further examine meteorological mechanisms by which mineral aerosol was transported to the PBL in the LFV, the MC2 model was modified to advect and diffuse a passive tracer. A 90 km grid resolution forecast was initialized 0000 UTC April 26, 1998, and 30 km and 10 km grids were run beginning 6 and 12 hours later, respectively. The 96 hour simulation ending at 0000 UTC April 30 was based on initial and boundary conditions from the National Centers for Environmental Prediction (NCEP) ETA model analyses. Vertically, the tracer was initially distributed as a 100 hPa deep (~1000 m) single layer, with a concentration maximum at 650 hPa, and no dust below the height of the 700 hPa pressure surface. This vertical distribution approximates serendipitous aircraft observations near Seattle on April 27, showing a distinct dust layer at about 2–3 km altitude and virtually no dust below [*Husar et al*., this issue]. Lidar backscatter data taken over Pasadena on April 27 [*Tratt et al*., this issue] showed layers at higher altitudes as well. However, multiple layers were excluded from the present simulation due to absence of complete tropospheric aerosol profile data over Washington State/British Columbia with which to confirm the presence of midtropospheric dust. Finally, the tracer was distributed homogeneously horizontally and was continuously supplied at the boundaries of the model domain.

Figures 7a, 7b show topographic contours and winds at 500 hPa and in the surface layer (10 m) during late afternoon on April 29 (0000 UTC, April 30). Vertical velocities within the surface layer at 0000 and 1200 UTC, April 29, and 0000 UTC, April 30 (1700 Pacific standard time (PST), April 29) are shown in Figures 7c, 7e, 7g, while the corresponding surface tracer concentrations (dimensionless) are shown in Figures 7d, 7f, 7h. Over the time period presented, it is evident that the tracer cloud was initially (Figure 7d) mixed to ground over the topography of western Washington State and southwestern British Columbia (the Cascade Range). Later, a secondary ground level maximum is observed in the northeastern portion of the domain over the Rocky Mountains (Figure 7f). On April 28 (Figures 7c, 7d), zones of high surface tracer concentrations are broadly coincident with regions of sinking motion in the

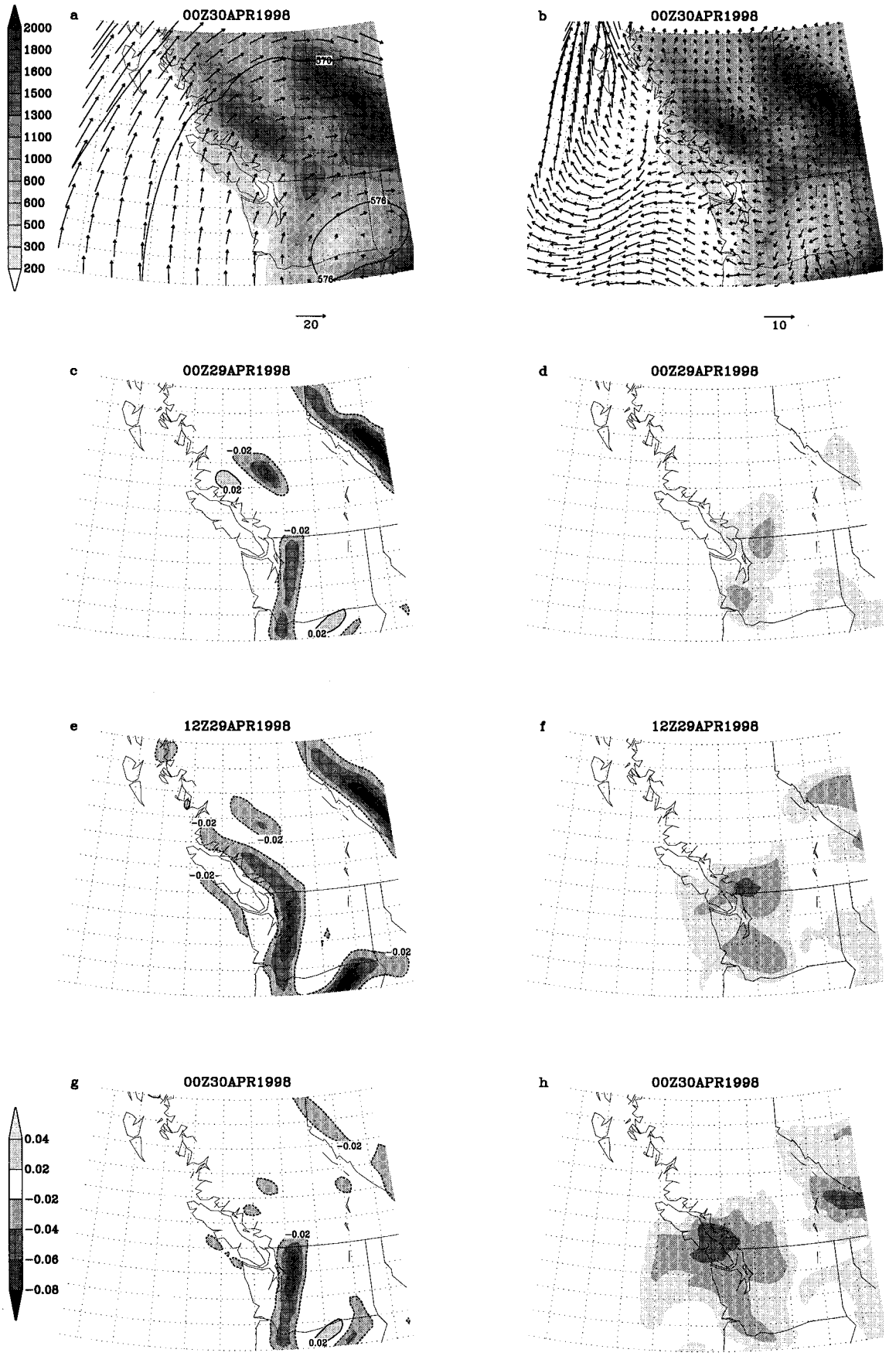

Figure 7. Numerical model simulation results from 0000 UTC, April 29, 1998 to 0000 UTC, April 30, 1998, showing (a) 500 hPa geopotential heights and wind vectors (m s^{-1}) overlaying topography (m), and (b) Surface (10 m) wind vectors and topography at 0000 UTC, 30 April. Below are couplets of panels showing (left) time sequence of surface layer vertical velocities (m s^{-1}, subsidence is negative) and (right) surface tracer concentrations (dimensionless, highest concentrations are darkest).

lower troposphere. However, to the northeast of Vancouver Island a region of subsidence associated with flow across the coast mountain range does not mix the tracer to the surface. This is attributed to strong divergence evident at 600 hPa and above in a swath running broadly parallel and southward of the 570 dam (dekameter) isoline in Figure 7a. This divergence (associated with an upper level jet) resulted in localized lifting of the tracer layer rendering it inaccessible to surface-based mixing processes. Consequently, down mixing of the aerosol layer was confined to the southern and western portions of the model domain where convergence and subsidence dominated.

A low-level ridge axis over the southwestern model domain, associated with synoptic scale subsidence, caused weak offshore flow near the surface throughout the simulation (Figure 7b). As a result, once mixed into the boundary layer from aloft, zones of peak surface tracer concentrations show a general trend of horizontal spreading and westward transport throughout the period. Modeled concentrations peak in the LFV region on April 29 and cross southern Vancouver Island by late on April 29 (PST).

Spatial and temporal patterns presented in Figure 7 are consistent with observations (Figure 2) showing concentrations peaking first in central southern British Columbia (April 28) and then later to the west. Furthermore, the simulation captures the zone of maximum concentrations observed on April 29 across central Washington State and southern British Columbia [*Husar et al*., this issue].

It is probable that intensity of subsidence and down mixing over the mountainous regions of southern British Columbia and Washington State, as shown by the MC2 model, was a significant factor contributing to the relatively high PM_{10} concentrations observed in these regions compared to those observed as far south as California [*Husar et al*., this issue]. Subsidence associated with the upper level ridge created sustained vertical velocities of the order of 0.05 m s^{-1} throughout the lower troposphere, with peak values more than twice that value. These sinking motions transported the tracer downward more than 2 km over half a day and permitted interception by the growing mixed layer over the mountainous interior of British Columbia and Washington State.

5. Discussion and Conclusions

Elemental composition data and model simulations indicate that during late April 1998, southwestern British Columbia and western Washington State experienced unusually high particulate concentrations and a pervasive yellow/white haze due to long-range transport of Asian dust to the region. Such events are undoubtedly rare because there is no evidence of similar dust incursions to western North America over the past decade. In the LFV this episode coincided with poor dispersion conditions and degraded air quality. Reconstructed soil mass and comparison with other spring meteorological analogs suggest that between ~38 and 55% of PM_{10} concentrations observed in the LFV at the peak of the episode were due to injection of Asian dust, while the remainder could be attributed to usual local sources. Elemental analyses and meteorological circumstances eliminate alternative sources (e.g., forest fires or local farm practices) as significant contributors to the episode.

Model results indicate that Asian dust was entrained into the PBL over the region by vertical mixing over the interior of southwestern British Columbia and central Washington State. A jet-induced swath of divergence aloft across northern British Columbia confined the down mixing event to a region southward of a line extending through central Vancouver Island to northern Alberta. Subsidence within the midtropospheric ridge of high pressure aligned along the coastline lowered elevated aerosol layers sufficiently to permit interception by surface-based mixing processes. Outflow (offshore) surface winds then transported Asian dust into the LFV where it added to the burden of locally generated particulate matter. This mechanism is consistent with the observed spatial and temporal patterns of PM_{10} concentrations.

The April 1998 particulate episode is the first documented case of LRT of Asian dust to southwestern British Columbia and raises questions about the frequency of such events and their potential impact on human health, visibility, and soil and water quality. However, given the rarity of such mineral dust events, the April 1998 episode is perhaps most significant in terms of the light it sheds on meteorological transport mechanisms likely to affect anthropogenic pollutants originating from the rapidly industrializing regions of Asia. Recently, *Jaffe et al*. [1999] described long-range transport of anthropogenic pollutants from eastern China to western Washington State for the first time. Long-range transport of such primary and secondary pollutants (e.g., NO_x and O_3) appear to be much more frequent than the mineral dust events described here and have the potential to offset the effects of domestic reductions in anthropogenic emissions in western North America [*Jacob et al*., 1999].

Finally, the magnitude of the April 1998 event and the confusion it generated in local media and in regulatory agencies suggests that protocols should be developed which alert air quality managers to information provided elsewhere by satellite monitoring of dust events. This information could be used in combination with standard meteorological analyses (including trajectories) and modeling to better predict such events and provide public information and advisories.

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