

# Trans-Pacific dust events observed at Whistler, British Columbia during INTEX-B

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**Abstract.** The meteorology and physico-chemical characteristics of aerosol associated with two new cases of long range dust transport affecting western Canada during spring 2006 are described. Each event showed enhancements of both sulfate aerosol and crustal material of Asian origin. However, the events were of quite different character and demonstrate the highly variable nature of such events. The April event was a significant dust event with considerable enhancement of fine particle sulfate while the May event was a weaker dust event, also with significant fine particle sulfate enhancement. The latter event was notable in the sense that it was of short duration and was quickly followed by a large increase of organic material likely of regional origin. Comparison of these two events with other documented cases extending back to 1993, suggests that all dust events show coincident enhancements of sulfate and crustal aerosol. However, events vary across a wide continuum based on the magnitude of aerosol enhancements and their sulfate to calcium ratios. At one extreme, events are dominated by highly significant crustal enhancements (e.g. the well-documented 1998 and 2001 “dust” events) while at the other are events with some dust transport, but where sulfate enhancements are of very high magnitude (e.g. the 1993 event at Crater Lake and the 15 May 2006 event at Whistler). Other events represent a “mix”. It is likely that this variability is a function of the comparative strengths of the dust and anthropogenic SO<sub>2</sub> sources, the transport pathway and in particular the extent to which dust is transported across industrial SO<sub>2</sub> sources, and finally, meteorological and chemical processes.

## 1 Introduction

During April–May 2006, INTEX-B (the Intercontinental Chemical Transport Experiment) was focused on the North Pacific with the goal of providing detailed chemical analysis of tropospheric air following a trans-Pacific pathway to the North American continent (e.g. Zhang et al. (2008) discuss ozone transport during INTEX-B). This intensive field campaign, involving ground based, airborne and satellite observations, was prompted by over a decade of observational and modelling studies demonstrating the relatively rapid (especially during springtime) trans-Pacific transport of both crustal material (predominately desert dusts) and anthropogenic pollutants from sources in Eurasia to North America (e.g. Jaffe et al., 1999, 2003; Husar et al., 2001; Holzer et al., 2003; Jacob et al., 1999). In this context, the mobilization and transport of mineral dust from the arid regions of the world is considered of major significance due to the role airborne crustal material plays in the global radiation balance (and hence climate forcing), cloud processes, atmospheric chemistry, oceanic and terrestrial biogeochemical processes (e.g. dust is a major source of iron and calcium), as vectors for microbes, and as a factor influencing local air quality in both “source” and “sink” regions (Prospero et al., 2002). Furthermore, recent studies suggest that dust participates in important interactions with anthropogenic pollutants such as sulfur-dioxide (SO<sub>2</sub> – a source of sulfate aerosol). Such pollutants are often mixed into, and interact with, the dust plumes as they pass over urban/industrial sources (Li-Jones and Prospero, 1998; Heald et al., 2006).



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Studies of trans-Pacific dust transport suggest a strong linkage between anthropogenic sulfate aerosol and crustal dust transport from Asia. For example, VanCuren's (2003) analysis of aerosol data at Crater Lake, (Oregon) and Mt. Lassen (California) shows that a mixture of dust and combustion products dominate Asian aerosol that arrives in North America. Their major constituent fractions of particles ( $<2.5\ \mu\text{m}$  diameter) were 30% mineral, 28% organic compounds, 4% elemental carbon, 10% sulfate,  $<5\%$  nitrate, and  $<1\%$  sea salt. Heald et al. (2006), using satellite imagery, GEOS-Chem model and Interagency Monitoring for Protected Visual Environments (IMPROVE) surface network data from the western USA, have also demonstrated the strong coincidence of crustal dust and sulfate aerosol in trans-Pacific pollutant transport. Springtime Asian sulfate aerosol enhancements are shown to be greatest in Washington State and southern British Columbia with maximum 24-h enhancements reaching approximately  $1.5\ \mu\text{g m}^{-3}$  (Heald et al., 2006). These results suggest that combined dust/sulfate transport events may have important implications for the setting and attainment of visibility standards in western North America. This is particularly relevant when set against a background of burgeoning emissions of  $\text{SO}_2$  from Asia, where not only have  $\text{SO}_2$  emissions increased by 119% between 1980–2003 (Ohara et al., 2007), but also Asian sulfate influx to North America has increased 72–85% between 1985–2006 (van Donkelaar et al., 2008). Streets and Waldhoff (2000) indicate that Asian  $\text{SO}_2$  emissions are projected to increase from 25.2 mt in 1995 to 30.6 mt in 2020 (assuming emission controls are implemented on large power plants) and possibly to 60.7 mt without emission controls.

Beginning with the well-documented 1998 dust episode, a growing inventory of trans-Pacific dust events affecting North America has been established. Most of these events have involved sources in the Gobi and Takla Makan deserts Asia (Husar et al., 2001; Jaffe et al., 2003, Thulasiraman, 2002), although recently, a case of Saharan dust transport across Asia and the Pacific to North America has been documented (McKendry et al., 2007). In addition, modelling studies have identified many aspects of the climatology, inter-annual variability and pathways of dust transport and deposition (Holzer et al., 2003, 2005; Gong et al., 2006; Zhao et al., 2006; Chin et al., 2007). The meteorological mechanisms associated with boundary layer – free tropospheric (BL-FT) exchange of dust (and anthropogenic pollutants) have also largely been identified. BL-FT exchange processes most relevant to dust source areas include the warm conveyor belt (WCB) mechanism (Cooper et al., 2004; Stohl et al., 2002) and frontal lifting, while in receptor regions (such as western North America) subsidence, and mountain wave activity are important in bringing mid-tropospheric dust layers in range of BL entrainment processes (McKendry et al., 2001; Hacker et al., 2001).

Against this background of improved understanding of many aspects of trans-Pacific dust transport, the intensive ob-

servations afforded by INTEX-B provide a further opportunity to extend the inventory of documented dust events and to examine the commonalities emerging from such a catalog of events. In this context, our goals in this paper are to:

- Describe two separate dust events identified during INTEX B
- Compare and contrast these events with previously documented cases, particularly with respect to their magnitude and chemical signature. For the latter, sulfate aerosol measurements during INTEX-B provide a rare opportunity to examine the linkage between sulfate and mineral aerosol in these cases.

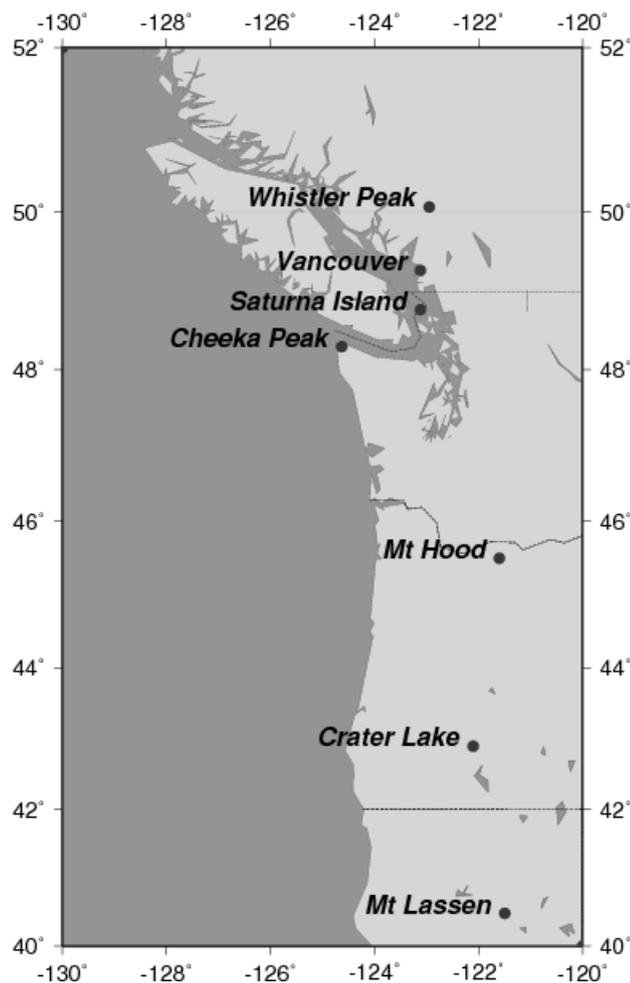
## 2 Methods

### 2.1 Whistler Peak

Measurements of particles and trace gases are made by Environment Canada at a high elevation site in Whistler, BC, approximately 100 km north of Vancouver (Fig. 1). The site is located at the top of a ski hill, at Whistler peak, 2182 m (above sea level). There are no continuous combustion sources at the peak and influences from snowmobiles have been identified and removed from the data set.

At the time of INTEX-B, the ongoing measurements at Whistler Peak were  $\text{O}_3$ , CO, particle chemistry, particle size distributions ( $0.01\text{--}20\ \mu\text{m}$ ), light scattering and light absorption. Particle chemistry consisted of 48 hour averaged filters cut at  $2.5\ \mu\text{m}$  and analyzed by ion chromatography (IC) for ions of chloride, nitrate, sulfate, sodium, ammonium, potassium, magnesium and calcium. Particle size distributions are measured using a Scanning Mobility Particle Sizing system (SMPS) for  $0.01\text{--}0.4\ \mu\text{m}$  diameter particles and a Grimm optical particle counter (OPC) (Model 1.108) for  $0.3\ \mu\text{m}$  to  $20\ \mu\text{m}$  particles. All particle sampling was through a stainless steel manifold. The manifold intake was heated to a minimum of  $4^\circ\text{C}$  in order to prevent riming of the intake when supercooled cloud was present. Temperatures were below  $4^\circ\text{C}$  about 60% of the time; the temperature record is given by Leitch et al. (2008). In addition, the aerosol was heated by the being drawn into the room with the instruments, such that the temperature of the aerosol at the point of measurement was approximately  $20^\circ\text{C}$  and outside air temperatures ranged from about  $-10^\circ\text{C}$  to  $15^\circ\text{C}$  during the study. Details of the on-going measurements at Whistler Peak are discussed by Macdonald et al. (2008).

In addition to the 48 h filters, there were two other measurements of particle chemistry at Whistler Peak during INTEX-B. Size segregated particle chemistry was also measured from samples collected from about 4 p.m. one day to 10 a.m. the next day using non-rotating MOUDI samplers reduced to three size cuts ( $<1\ \mu\text{m}$ ,  $1\text{--}3\ \mu\text{m}$  and  $>3\ \mu\text{m}$ ). The size segregated samples were averaged only during the 18 h



**Fig. 1.** Map showing study area and places mentioned in the text.

overnight period in order to reduce the influence of the daytime boundary layer on the samples. The size segregated samples were analyzed by IC for the same ions as the 48 h samples plus oxalate, acetate and formate. The MOUDI sampler was mounted outside so that particles entered directly into the impactor. Fine particle chemistry (fine particles defined here as  $<1 \mu\text{m}$  diameter) was measured using an Aerodyne High Resolution Time-of-Flight Aerosol Mass Spectrometer (HR-ToF-AMS). The observations from the HR-ToF-AMS are discussed by Sun et al. (2008).

## 2.2 Cessna

Measurements of  $\text{O}_3$  (TECO 49), CO (Aerolaser), physical and chemical size distributions of aerosol particles were conducted from a Cessna 207. The physical size distributions of the aerosol particles were measured with a Particle Measuring Systems (PMS) 7610 Condensation Particle Counter (CPC; particle number concentration  $>15 \text{ nm}$ ), a PMS Passive Cavity Aerosol Spectrometer Probe (PCASP100X;

$0.12\text{--}3 \mu\text{m}$ ) and a Forward Scattering Spectrometer Probe (FSSP300;  $0.3\text{--}20 \mu\text{m}$ ). The CPC was mounted inboard the Cessna and the PCASP100X and FSSP300 were both mounted in pods under the wings of the aircraft. The PCASP uses an intrusive sampling system, such that the particles are at least partially dried prior to detection, whereas the FSSP uses a non-intrusive system to sample the particles (e.g. Strapp et al., 1992). The chemical size distribution was measured with an Aerodyne Quadrupole Aerosol Mass Spectrometer (Q-AMS) located inboard. The Q-AMS is used to measure mass concentrations of classes of compounds (e.g. sulfate, nitrate, ammonium and total organics). Particles between about  $0.1 \mu\text{m}$  and  $0.7 \mu\text{m}$  are efficiently transmitted into the Q-AMS (e.g. Liu et al., 2007). Fundamentals of the Q-AMS are described by Jayne et al. (2000). The aerosol was supplied to the inboard instrumentation using an open ended  $0.95 \text{ cm}$  OD stainless steel tube. The tube was supported outside of the aircraft and elevated about  $0.5 \text{ m}$  from the top of the fuselage. Ram pressure from the aircraft pushed the aerosol into and through the tubing; the end of the tubing was open to the cabin. Both the Q-AMS and CPC sampled from this inlet. Flights were approximately two hours long, and most flights consisted of ascent and descent profiles at Whistler to an altitude of about  $5.3 \text{ km}$ . Data were recorded every second, except for the AMS data that were recorded as one-minute averages in order to try to optimize for temporal resolution and sufficient signal for detection. Further details of the instrumentation and comparisons are given by Leitch et al. (2008).

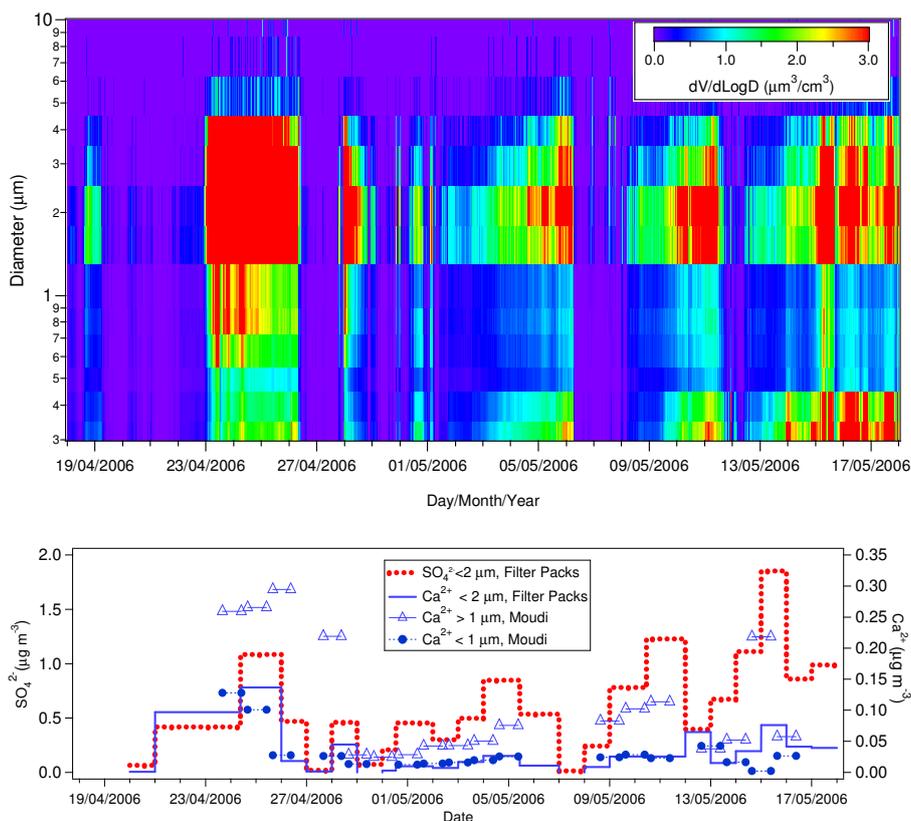
## 2.3 Modelling

GEOS-Chem v7-04-09 at  $2^\circ \times 2.5^\circ$  ([www.as.harvard.edu/chemistry/trop/geos/](http://www.as.harvard.edu/chemistry/trop/geos/)) was used to estimate dust emissions and transport from Asia to North America. It is driven using assimilated meteorological data from the Goddard Earth Observing System (GEOS-4) at the NASA Global Modeling Assimilation Office (GMAO). The dust module is described in detail by Fairlie et al. (2007) and includes the effects of gravitational settling as well as wet and dry deposition.

## 2.4 Ancillary data

Crater Lake and Mount Hood are part of the Interagency Monitoring of Protected Environments (IMPROVE) network of stations (<http://vista.cira.colostate.edu/improve/Default.htm>) where aerosols are collected on filters (24 h samples) every third day (since 2000). Samples are analysed for elemental composition and are reported in fine ( $\text{PM}_{2.5}$ ) and coarse ( $\text{PM}_{2.5-10}$ ) fractions.

The Dalhousie Raman Lidar (DRL) is described by Duck et al. (2006) and was available at Whistler for the 15 May event only. It transmits an  $11 \text{ W}$  pulsed laser beam at  $532 \text{ nm}$  wavelength vertically into the atmosphere and employs a  $25 \text{ cm}$  diameter telescope with  $1 \text{ mrad}$  field-of-view in the



**Fig. 2.** (a) Two dimensional image plot of particle volume distributions from the Grimm optical particle counter at Whistler Peak from 18 April to 18 May 2006. (b) Time series of sulfate and calcium collected from filter packs (<2.5 microns) and calcium collected from Moudi impactors (<1 micron and >1 micron).

receiver. The received photons are separated into 532 nm (elastic) and 607 nm (1st Stokes nitrogen Raman) wavelength channels through the use of an interference-filter based polychromator and detected using photomultiplier tubes and fast counting electronics.

### 3 Results

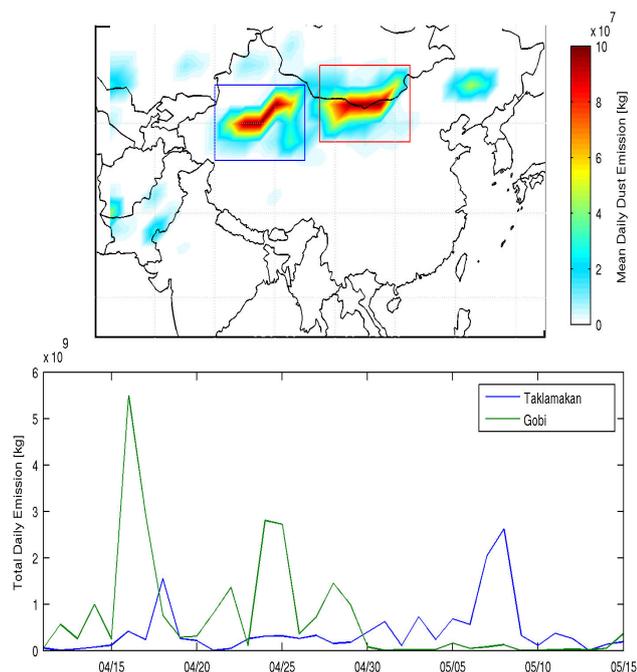
#### 3.1 Dust events at Whistler

Observations at Whistler Peak from 23 April to 17 May 2006 show at least five distinct episodes of increased coarse particle number concentrations (Fig. 2a, b). Calcium in the coarse particle samples collected at Whistler Peak using the MOUDI show significant enhancements during the 22–26 April period as well as on 15 May. Calcium is also higher on 4 and 8–10 May; no samples were collected on 5, 6, 7 or 11 May. The mass concentration of coarse particle calcium on 28 April was the second lowest measured during the period, and the increase in coarse particle number concentrations on 28 April is connected to the boundary layer based on the aircraft profiles from that day. The episodes of late April,

2–5, 9–10 and 15 May are consistent with observations of sand/dust storm events (SDS) in Northeast Asia (Zhou et al., 2008), Aeronet observations from Saturna Island (location in Fig. 1) and modeling results described by Zhao et al. (2007). Of these four episodes, the highest magnitude, both in terms of particle number and calcium mass, occurred from 23–26 April at Whistler and was associated with material with modal particle diameter in the range of 2–4  $\mu\text{m}$  (Fig. 2 and Leitch et al., 2008). The second highest, again both in number and calcium mass, occurred from 15–16 May (Fig. 2). Both events were in broad agreement in terms of magnitude and timing with NAAPS forecasts for Cheeka Peak (available at <http://www.nrlmry.navy.mil/aerosol/>), an atmospheric chemistry monitoring site in the US just south of Vancouver Island. Based on the magnitude of the 23–26 April and 15–16 May dust events at Whistler, and their connection with sulfate aerosol (Fig. 2b), these two events provide the focus of this study.

#### 3.2 Meteorology and Asian dust storms

GEOS-Chem was used to estimate dust emissions and transport from Asia to North America. The top panel of Fig. 3



**Fig. 3.** Simulated dust emissions over East Asia during INTEX-B. The top panel shows average emissions for this period. The bottom panel shows temporal variation of total daily emissions within the regions outlined in the upper panel.

shows simulated daily mean dust emissions over China between 6 April and 19 May 2006. The bottom panel plots simulated total daily dust emissions within enhancement regions, as outlined within the blue and red boxes, and corresponding to the Taklamakan and Gobi deserts, respectively. Significant dust emissions are produced on 16 April, 24–25 April and 7–8 May. The Asian dust storms of 16 April and 7–8 May, are the likely origin for the dust events observed at Whistler Peak on 23–26 April and 15–16 May. Zhou et al. (2008), in an inventory of SDS activity in 2005 and 2006, also note severe SDS activity in the period 15–19 April 2006 in Mongolia that influenced regions including northern China, the Korean Peninsula and Japan. High emissions of dust evident in the period 24–25 April in Fig. 3, did not result in significant transport to the Canadian west coast due to inauspicious meteorology. In this case, trans-Pacific transport of crustal material was relatively weak with a zonal trajectory to the south of Whistler (NAAPS archive – available at <http://www.nrlmry.navy.mil/aerosol/>).

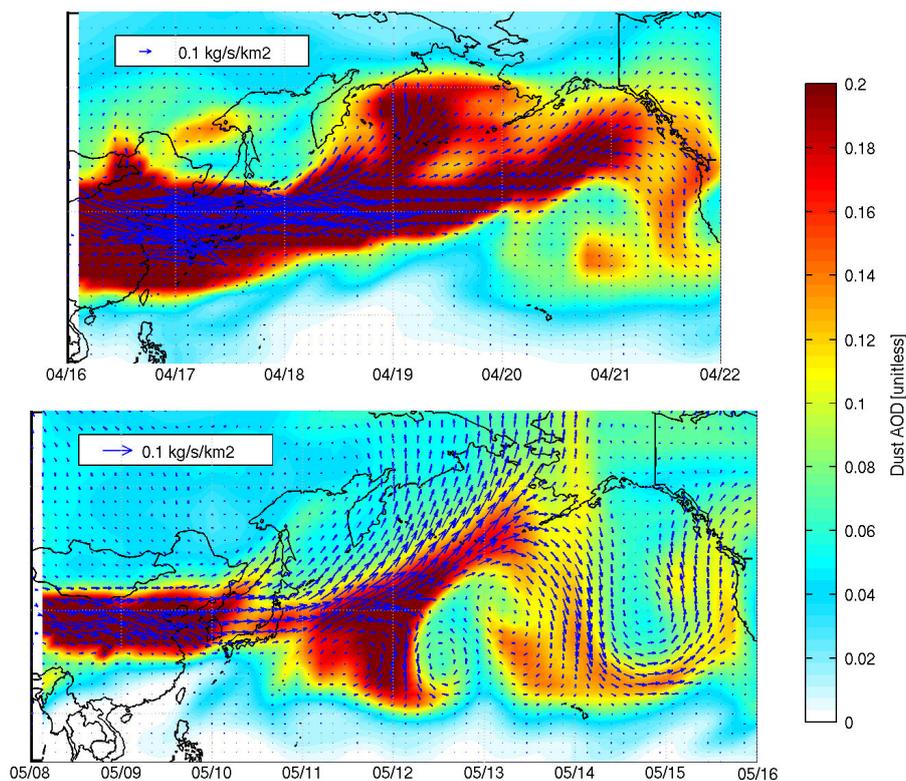
Figure 4 shows the simulated transport across the Pacific Ocean of dust aerosol generated from the 16 April and 8 May emission events. To concisely represent plume flow, Fig. 4 is generated by regularly sampling the simulated aerosol optical depth of dust at constant longitudinal spacing from the emission date until arrival at Whistler Peak. As in previously documented dust incursions (Husar et al., 2001; Jaffe et al., 2003; McKendry et al., 2007) both events involved

direct transport across the Pacific in well-developed zonal flow. Both cases took approximately one week for transport and are consistent with the most probable trans-Pacific mid-tropospheric transit times of 6–8 days calculated by Holzer et al. (2005). Columnar flux patterns, shown as blue arrows on Fig. 4, suggest two distinct pathways taken during transport, with the April event arriving at Whistler Peak via a northerly route and the May event from the south. This may be an important factor contributing to differences in the chemical signatures of the two events (see below).

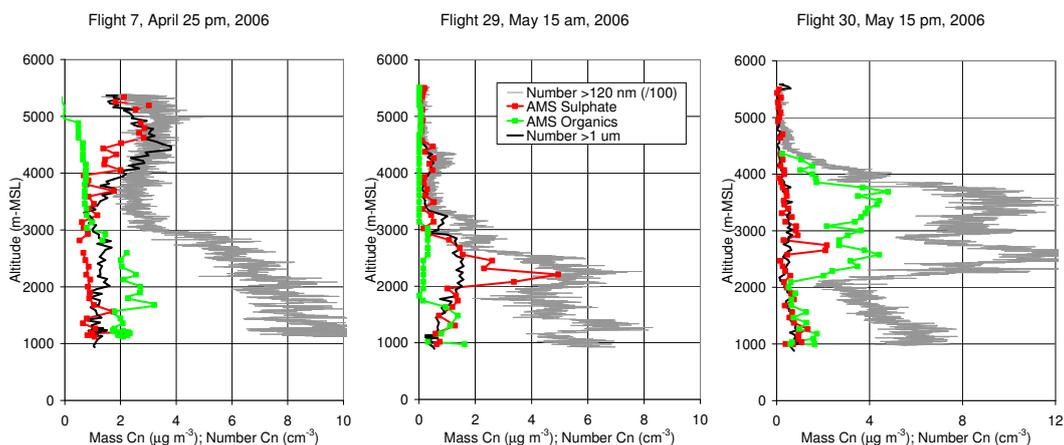
### 3.3 Whistler observations: vertical profiles and lidar

Vertical profiles of particle counts, and sulfate and organic aerosol concentrations derived from Cessna flights on 25 April and 15 May are shown in Fig. 5a–c. The 25 April fine particle aerosol profile (Fig. 5a) is marked by two distinct components. In the boundary-layer (BL), which extended to about 3 km based on the vertical distribution of sulfates, organics and particle number concentrations, the fine particles were composed of about 60% organic material, 30% sulfate, and much of the balance was made up by nitrate and ammonium. Above 3 km, the fine particle aerosol was almost completely dominated by sulfate. Coarse particle chemistry during INTEX-B was measured only at Whistler Peak (Leaitch et al., 2008). The number concentrations of particles  $>1 \mu\text{m}$  (i.e. PCASP and OPC) were higher above 3 km and much lower in the boundary-layer, consistent with the transport of dust from Asia. The presence of a predominantly sulfate aerosol is also consistent with past observations (e.g. Brock et al., 2004) and other observations during INTEX-B (e.g. Peltier et al., 2008; Dunlea et al., 2008; van Donkelaar et al., 2008), and suggest that the aerosol was formed by the oxidation of  $\text{SO}_2$  during transport, in both cloud and the gas phase. The fine particles above 3 km were also larger than those in the boundary layer. This is evident in the PCASP size distributions (Leaitch et al., 2008) and from Fig. 7; the reduction in particle number concentrations from the BL to above 3 km is about a factor of four whereas the reduction in the fine particle mass is a factor of two or less. An increase in the size of the fine particles is an indication of a longer lived aerosol, which is consistent with trans-Pacific transport. Ozone is relatively high in the BL, and it increases from about 65 ppbv at 3 km to about 70 ppbv at 4.7 km. It increases another 10 ppbv in the plume between 4.7 and 5.2 km, evidence that photochemical production of ozone accompanied the production of sulfate. The INTEX-B observations were interpreted with a global chemical transport model (GEOS-Chem) to estimate that Asian anthropogenic emissions during the period increased the mean profiles observed over Whistler for fine particle sulfate by 56% (van Donkelaar et al., 2008) and for ozone by 6–8 ppbV (Walker et al., 2008).

As discussed by Sun et al. (2008), a predominantly sulfate plume impacted the Peak site on the morning of 15 May (Fig. 5b). The profile data show an increase in sulfate



**Fig. 4.** Transport pathways of East Asian dust plumes. Both panels show the simulated dust component of aerosol optical depth sampled at the dates shown, approximately following plume flow between simulated emission and observation at Whistler Peak. Arrows denote columnar flux magnitude and direction.

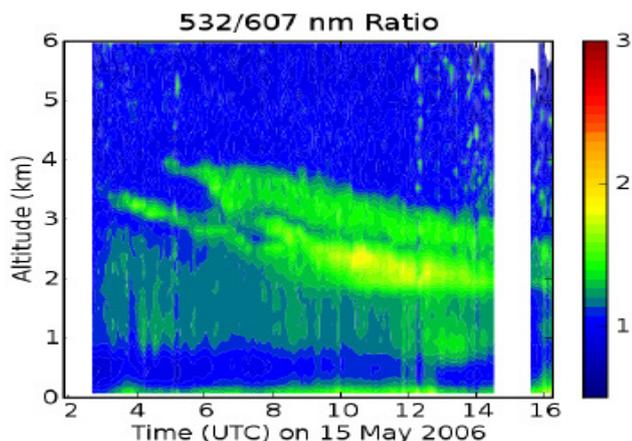


**Fig. 5.** Vertical profile data of sulfate and total organic fine particle mass concentrations (measured with a quadrupole AMS) and the number concentrations of aerosol particles larger than 120 nm diameter and larger than 1  $\mu\text{m}$  diameter. Note: the number concentrations of particles >120 nm are divided by 100.

between 2 km and 2.5 km at an elevation coincident with Whistler Peak. Accompanying this was a modest increase in  $\text{O}_3$  and a substantial increase in CO (Leaitch et al., 2008).

Lidar imagery from the morning of 15 May 2006 (Fig. 6) confirms the presence of an aerosol layer at approximately

the elevation of the Peak station (2182 m a.s.l.) and is in agreement with the profile data at this time (Fig. b). The backscatter ratio shown in Fig. 6 is calculated by dividing the 532 nm (elastic) signal by the 607 nm (molecular) signal and normalizing to unity in a region of clear air. Aerosols are



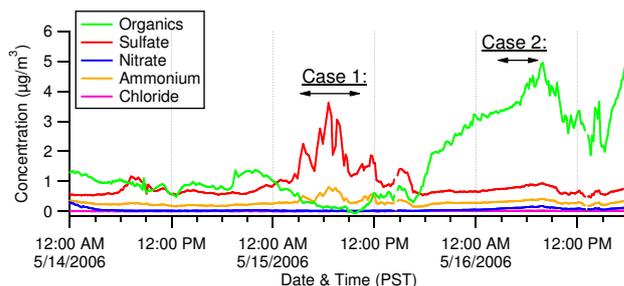
**Fig. 6.** Lidar imagery showing subsiding aerosol layer (Green) at Whistler on 15 May 2006.

identified by backscatter ratios greater than one. Note that the backscatter ratios presented are not corrected for the differential absorption between wavelengths due to aerosols and molecules. During the course of the 15 May event, lidar suggests that subsidence was a significant process bringing the sulfate-rich aerosol layer to mountain ridge level. The importance of subsidence in bringing dust layers in reach of the planetary boundary-layer over mountainous regions of western North America was identified by Hacker et al. (2001).

The situation changed dramatically by the afternoon of 15 May (Fig. 5c). While there was still a thin sulfate plume similar to that during the morning, the fine particle aerosol was clearly dominated by organics between 2 km up to about 4.4 km. This abrupt change was also seen in the Peak data (Fig. 7, case 2). Trajectories for this time indicate subsiding air at the 2–5 km level, with origin from the south to south west over the previous one to two days. Longer range trajectories come from the mid-Pacific and northern China (Fig. 4). Sun et al. (2008) attribute the origin of the organic plume (Case 2, Fig. 7) to regional sources with likely contributions from the urbanized regions extending from southern Puget Sound to Georgia Strait (Seattle – Bellingham-Vancouver) with possible contributions from biomass burning that was evident along the California-Oregon border during the period (<http://map.ngdc.noaa.gov/website/firedetects/viewer.htm>). In addition, given elevated tree emissions in the Whistler valley during the time period, biogenic secondary organic aerosol might also have contributed to the observed enhancement of organic aerosol mass.

### 3.4 Comparison with previously documented cases

In order to compare the dust events observed at Whistler during April–May 2006 with other documented dust events, IMPROVE data from the closest high altitude sites, with a sufficiently long record to encompass the Spring 1993 event,



**Fig. 7.** Time series of the mass concentrations of total organic, sulfate, nitrate, ammonium and chloride in the fine particles as measured at Whistler Peak using a high-resolution time-of-flight Aerosol Mass Spectrometer (W-TOF AMS). From Zhang et al. (2008).

were examined (Crater Lake, and Mt Hood, Oregon). Crater Lake is considered to be a pristine high altitude site that has been used in previous studies to examine trans-Pacific transport (Jaffe et al., 2005; Van Curen and Cahill, 2002; Zhao et al., 2008) and at approximately 2000 m, it is of similar elevation to Whistler. Furthermore, Ca (an important element of the crustal dust signature along with Si, Fe and Al) and  $\text{SO}_4$  concentrations measured as part of fine aerosol IMPROVE monitoring are comparable to the Moudi sampler measurements made at Whistler.

Documented trans-Pacific dust events (including those of 2006) are listed in Table 1. At Whistler, Ca concentrations reached  $0.14 \mu\text{g m}^{-3}$  on 24 April 2006 and were the highest since the start of record in 2002 (Fig. 2b). Concentrations during the May event were approximately half this value. Sulfate concentrations at Whistler for the 23–26 April and 15 May events reached  $1.1$  and  $1.8 \mu\text{g m}^{-3}$  respectively (Fig. 2b). For comparison, the monthly geometric mean sulphate and calcium concentrations measured at Whistler for April and May from 2002–2006 range from  $0.06 \mu\text{g m}^{-3}$  to  $0.40 \mu\text{g m}^{-3}$  and  $3 \text{ ng m}^{-3}$  to  $11 \text{ ng m}^{-3}$  respectively (Macdonald et al., 2008b). When placed in the context of the longer term record from Crater Lake, these dust events pale in comparison to the large events of 1998 and 2001 when calcium concentrations were enhanced by factors of 30–40 over mean background levels. However, the dust event of 23–26 April 2006 observed at Whistler (and apparent at Crater Lake) appears to be one of the largest 4–5 events observed over the thirteen year period. The May 2006 dust event on the other hand, is of low magnitude with concentrations comparable to the Saharan dust episode observed in 2005 (McKendry et al., 2007).

For all events listed in Table 1, aerosol sulfate concentrations at Crater Lake were enhanced over annual mean background concentrations by factors in the range 2–5.6. This is smaller than the range of enhancements shown for crustal dust and likely reflects the relatively constant anthropogenic source strength for Asian  $\text{SO}_2$  compared to the

**Table 1.** Crater lake Oregon and Whistler fine particle data. Comparison of documented trans-pacific dust events 1993–2006 with respect to relative importance of dust versus sulfate.

Date of arrival on west coast	Crater lake (1996 m) $\mu\text{g m}^{-3}$			Crater lake enhancement factor over mean		Whistler (2100 m) $\mu\text{g m}^{-3}$		Related publications
	Ca	SO <sub>4</sub>	SO <sub>4</sub> / Ca ratio	Ca	SO <sub>4</sub>	Ca	SO <sub>4</sub>	
28 April 1993	0.12	1.74	14.5	6.2	5.6			Jaffe et al. (2003)
29 April 1998	0.82	1.31	1.6	41.1	4.2			Husar et al. (2001), Tratt et al. (2001)
16–24 March 1999	0.06	0.69	11.5	3.0	2.0			NRL Case Study
16 April 2001	–	1.18	–	–	3.8			Jaffe et al. (2003), Thulasiraman (2002), Heald et al. (2006)
	0.40*	(0.95*)	2.4*	31*	(2.4*)			
15 March 2005	0.10	0.68	6.8	5.1	2.2	0.05	0.7	McKendry et al. (2007)
23–26 April 2006	0.20	0.93	4.7	9.9	3.0	0.14	1.1	this work, van Donkelaar et al. (2008), Macdonald et al. (2008), Leaitch et al. (2008), Zhang et al. (2008)
15 May 2006	0.05	0.81	16.2	2.6	2.6	0.08	1.8	this work, van Donkelaar et al. (2008), Macdonald et al. (2008), Leaitch et al. (2008), Zhang et al. (2008)

\* Mt. Hood Oregon (1531 m) values

highly variable dust sources. Of particular note is the large magnitude 15 May 2006 sulfate aerosol event that produced concentrations at Whistler peak ( $1.8 \mu\text{g m}^{-3}$ ) exceeding the maximum sulfate aerosol associated with documented crustal dust events observed at Crater Lake ( $1.74 \mu\text{g m}^{-3}$  on 28 April 1993). Crater Lake sulfate concentrations on 15 May were relatively low compared to those at Whistler. This is likely a result of the northward trajectory of the aerosol along the Pacific coast during this event (Fig. 4) and suggests that the sulfate plume had less impact at Crater Lake in this case. Elevated sulfate concentrations in plumes above 2 km at Whistler were seen on several flights. In these plumes, the coarse particle concentrations were always found to increase relative to above and below, but the levels varied considerably. The highest coarse particle concentrations were in plumes sampled from 22–26 April 2006 and then on 15 May 2006; lower values were measured during 2–5 May 2006 (Leaitch et al., 2008). Certainly some significant elevated sulfate plumes were seen with relatively little or no dust.

Ratios of SO<sub>4</sub> to Ca fine aerosol at Crater lake (Table 1) indicate some measure of the “mix” of aerosol for the different events, and together with enhancement factors, provide the basis for a somewhat subjective characterization of “events” with respect to the relative mix and magnitude of the sulfate vs mineral dust components. On this basis it is possible to de-

fine major dust events (29 April 1998, 16 April 2001, 23–26 April 2006) in which there was low to moderate sulfate enhancement. In other cases, the event incorporated dust but was a significant sulfate event (28 April 1993 at Crater Lake and 15 May 2006 at Whistler). Other cases (16–24 March 1999, and the Saharan dust event of 2005) are clearly of a more mixed nature with neither the sulfate or dust enhancements being particularly pronounced.

#### 4 Discussion and conclusions

During INTEX B, two significant aerosol events incorporating Asian dust were observed at Whistler Peak and in nearby aircraft profiles over southwestern British Columbia. Both events showed enhancements of both sulfate aerosol and crustal material of Asian origin. However, the events were of quite different character and demonstrate the highly variable nature of such events. The April episode was a significant dust event (one of the largest 4–5 events over the previous 13 years) with considerable sulfate enhancement while the May episode was a weaker dust event also with significant fine particle sulfate enhancement at Whistler peak (but not at Crater Lake). The latter event was interesting in the sense that it was of short duration and was quickly followed by significant enhancement of organic material likely of regional

origin. Although a thorough analysis of the significance of sulfate is outside the scope of this study, evidence was presented that East Asian enhancements of sulfate episodically degrade western Canadian surface air quality by as much as  $1.5 \mu\text{g m}^{-3}$ .

In terms of the meteorology of the two dust events observed during INTEX B, both were traceable to typical spring dust storms in China and shared the common pattern evident in previously documented cases (e.g., Husar et al., 2001; McKendry et al., 2005) of subsidence over western North America. Trajectories in the eastern Pacific were quite different in the two cases and were likely responsible for the differences in chemical “signature” of the two events. In contrast to the northerly approach to western North America in the April case, the May 2006 episode trajectory approached British Columbia from the south. As the trajectory became more southerly late on 15 May, the composition of the fine particle aerosol at Whistler Peak switched from high sulfate (likely of Asian origin) to high organic concentrations. It is believed that most of that fine particle organic mass was from regional sources over western North America and to the south of Whistler.

In summarizing the documented Asian dust events in Western North America, it is apparent that, in agreement with Heald et al. (2006), all dust events appear to show coincident enhancements of sulfate and crustal aerosol. However, events appear to vary across a wide continuum based on the magnitude of aerosol enhancements and their ratios. At one endpoint are events dominated by highly significant crustal enhancements (e.g. the well documented 1998 and 2001 “dust” events) while at the other end of the spectrum are events with some dust transport, but where sulfate enhancements are of very high magnitude (e.g. the 1993 event at Crater Lake and the 15 May 2006 event at Whistler). Other events lie somewhere between. It is likely that this variability is a function of:

1. the comparative strengths of the dust and anthropogenic  $\text{SO}_2$  sources
2. the transport pathway and in particular the extent to which dust is transported across industrial  $\text{SO}_2$  sources
3. meteorological and chemical processes. Of particular importance are the effects of precipitation, and the occurrence of favourable mid-tropospheric meteorological transport conditions (Holzer et al., 2005).

The coincident transport of sulfate and mineral aerosol evident in these events has potential implications for air quality compliance and visibility in western North America, and is likely evolving due to changes in land-use and anthropogenic emissions in Eurasian source regions. Furthermore, transport of sulfate and dust from Asia may have significant impacts on climate due to changes in particle size distributions and increased residence times of particles in the atmosphere.

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