New measurements of black carbon at the Whistler high elevation site.

Introduction

A major component of soot particles formed during incomplete combustion is a refractory material often called black carbon (Kleeman et al., 2000). Most atmospheric black carbon is formed during open burning or during the combustion of fuels for energy production. Open burning, primarily of forests and savannas, but also including agricultural waste, is the largest contributor to black carbon production. Combustion for energy production makes up most of the remainder of global black carbon emissions. The majority of emissions of this second type come from fossil fuels such as coal or diesel which are burned in industrial, transportation, or residential applications. Some contribution is also made by biofuels, such as wood, being burned in residential and small-scale industrial applications (Bond et al., 2004)

Particulate matter containing black carbon is important in the atmosphere because it both scatters solar radiation (Ramanathan & Carmichael, 2008) and strongly absorbs light in the mid-visible to near-infrared range of the spectrum (Bond and Bergstrom 2006). This has important implications on both local and global scales.

On a global scale, absorption of both direct and reflected solar radiation leads to a significant warming of the lower atmosphere (Ramanathan & Carmichael, 2008). Absorption of direct solar radiation can also cause an effect known as global dimming, where the total amount of sunlight reaching the earth`s surface is reduced (Ramanathan & Carmichael, 2008). Both of these effects have the potential to cause significant perturbations in the hydrological cycle.

In addition to absorbing and scattering light in the atmosphere, black carbon also impacts climate through deposition on snow or ice surfaces. This reduces their albedo and increases their absorption of solar radiation, leading to increased melting and an overall reduction of the planetary albedo (Ramanathan & Carmichael, 2008).

On a more local scale, high concentrations of particulate matter from incomplete combustion can adversely affect both visibility (McMeeking, et al., 2005) and human health (Nel, 2005). High concentrations of soot particles can significantly affect visibility by scattering and absorbing visible light. Incomplete combustion also produces primarily fine and ultrafine particles (those less than 2.5 and 0.1 μm respectively) which can penetrate significantly into the respiratory system. These particles often consist of black carbon core with a coating of other material, any of which may have negative health impacts (Nel, 2005).

Experimental

Sampling Site

The Whistler high elevation site is a year round atmospheric sampling facility operated by Environment Canada at the peak of Whistler mountain ($50^{o}06'$N, $122^{o}96'$W, 2182 m

a.s.l). This site is uniquely situated in that it often sits within the free troposphere providing an opportunity to sample background particulate matter as well as particulate matter carried across the Pacific from the east coast of Asia. Even when the site is within the boundary layer, it experiences very little influence from any major metropolitan area and provides a unique opportunity to measure the impact of biomass burning events that typically occur in the wilderness surrounding the site during the dry summer months.

Instrumentation
Refractory black carbon (rBC) was measured at the Whistler high elevation site with a single particle soot photometer (SP2). The SP2 measures the mass of refractory black carbon by means of laser induced incandescence on a single particle level. Air, containing rBC, is sampled at an average flow rate of 2 cm^3/second and is introduced into an intracavity Nd:YAG laser operating at 1064nm in the TEM_{00} (Gaussian beam profile) mode. When an rBC particle intersects the laser beam, the particle is quickly heated to its incandescent temperature due to black carbon's ability to efficiently absorb light at 1064 nm. The visible light emitted from an incandescing particle is collected on two photomultiplier tubes (PMTs), each optically filtered such that one "broadband" channel collects signal from 350-800 nm and one "narrowband" channel collects signal from 630-800 nm. The ratio of these two incandescent signals provides information on the boiling point temperature and can be used for identifying rBC and other particles that absorb at 1064 nm. The peak amplitude of the "broadband" incandescent signal is also directly proportional to the mass of the rBC particle and time resolved mass can be determined for individual rBC particles with mass equivalent diameters from approximately 65 nm to 300 nm, the detection limits for the SP2 used for this analysis.

Results

New measurements of black carbon were carried out at Whistler peak for the period of April 1 – July 31, 2012 (Figure 1) using UBC's new single particle soot photometer. The data shown have been binned in 10 minute intervals and filtered for local contamination (such as snow grooming equipment operating near the sample site) by eliminating sudden increases in particle number that are fourfold or higher compared to the average of the preceding hour. The rBC mass concentration ranged from 0.01 ng/m^3 on June 7th to 139.0 ng/m^3 on June 21st with an average value of 9.6 ng/m^3.

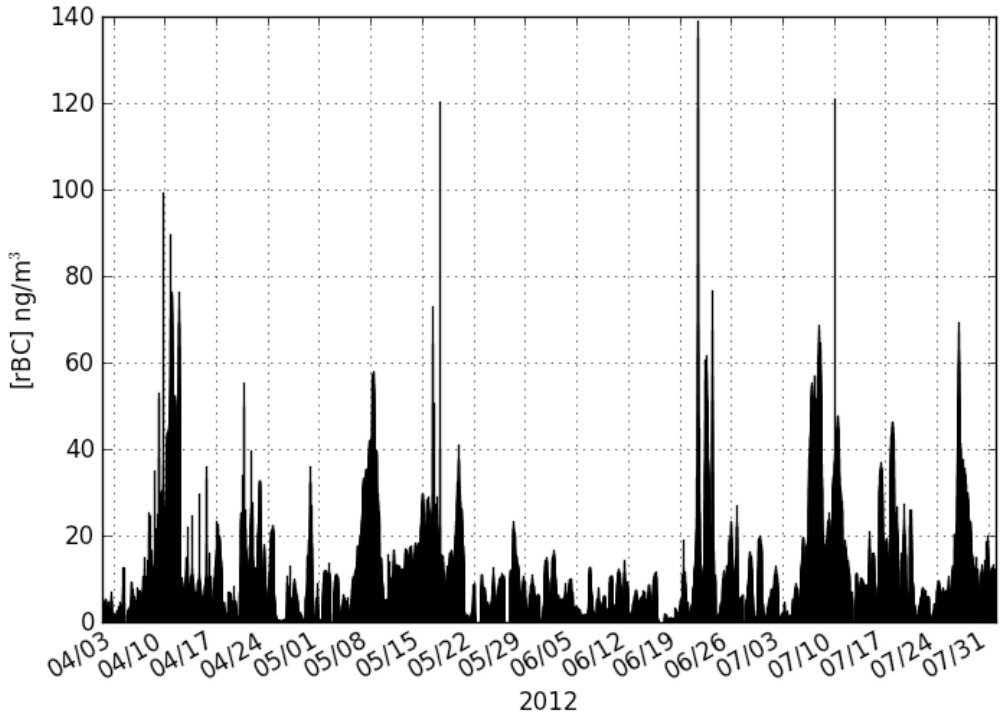

Figure 1. Refractory black carbon mass concentrations measured from April 1 to July 31, 2012. The data have been binned into 10 minute intervals. Measurements impacted by local contamination have been removed.

Figure 2 shows the frequency distribution for the rBC mass concentration data in Figure 1. It can be seen that the mass concentration was primarily less than 25 ng/m^3 with almost no occurrence of mass concentrations over 50 ng/m^3.

In Appendix 2 these measurements are put into the context of measurements made at the Whistler high elevation site between June, 2009 and July, 2012.

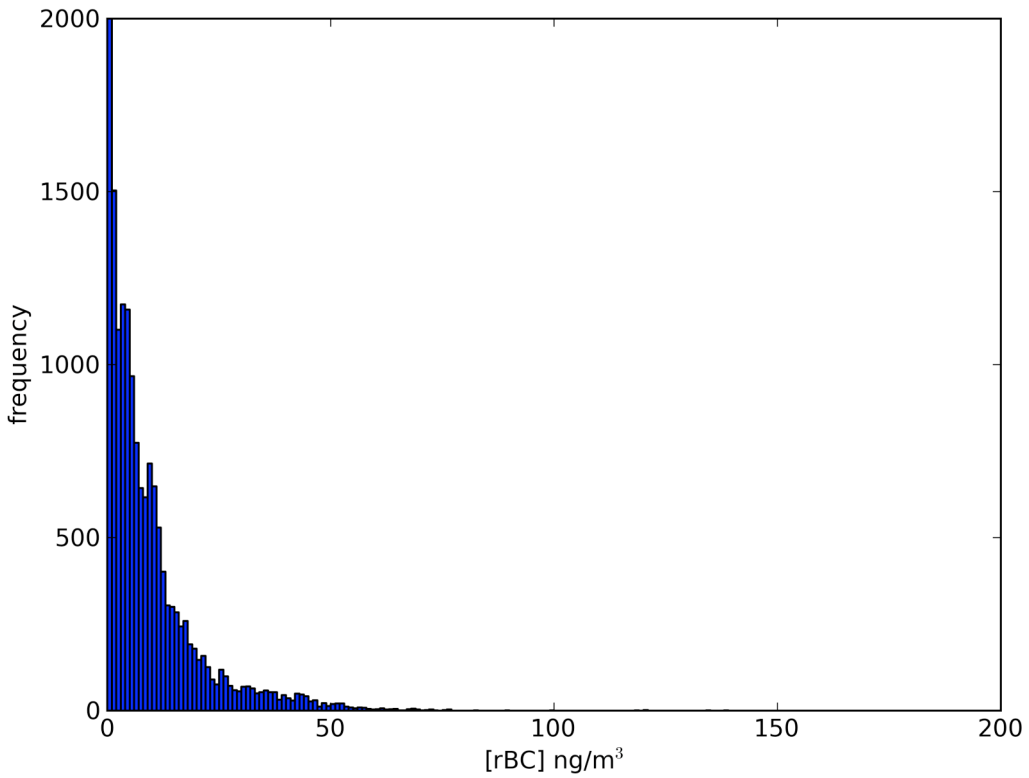

Figure 2. Frequency distribution for the rBC mass concentration data shown in Figure 1.

Appendix 2: *Three-year record of black carbon measurements at Whistler Peak from June, 2009 to July, 2012.*

Results:

In this section we have compiled black carbon data that was collected at the Whistler high elevation site over a three year period. Figure 3 shows a time series for the rBC mass concentrations measured between June 27th 2009 and July 31st 2012. It should be noted that the 2009 and 2010 data were collected on a different SP2 instrument and processed slightly differently than the 2012 data. In 2012 the UBC SP2 was used and the lower limit for detectable black carbon mass was set as 0.25 fg, the size of the smallest calibration standard used. This corresponds to an ambient particle volume equivalent diameter of approximately 64 nm. The 2009 and 2010 measurements were made with an SP2 belonging to Environment Canada and a lower limit of 100 nm volume equivalent diameter was used.

From Figure 3 it can be seen that the 2012 mass concentrations are similar in magnitude to the 2010 data, and slightly lower on average than the 2009 levels. In 2009 two biomass burning periods were identified and accounted for the highest mass concentrations seen. These two periods in 2009 were identified as being primarily influenced by biomass burning using a combination of metrics. The number of fires occurring within a 200km radius of Whistler was greater than 10, there was increased detection of levoglucosan (a thermal breakdown product of cellulose often used as a biomass burning marker), and the ratio of particle organic matter to particle organic matter + sulfate was greater than 70% (and indicator of non-anthropogenic sources). (see our BC-CLEAR Report 1 for more details). No biomass burning analysis was done for 2012, but this may account for some of the differences observed here.

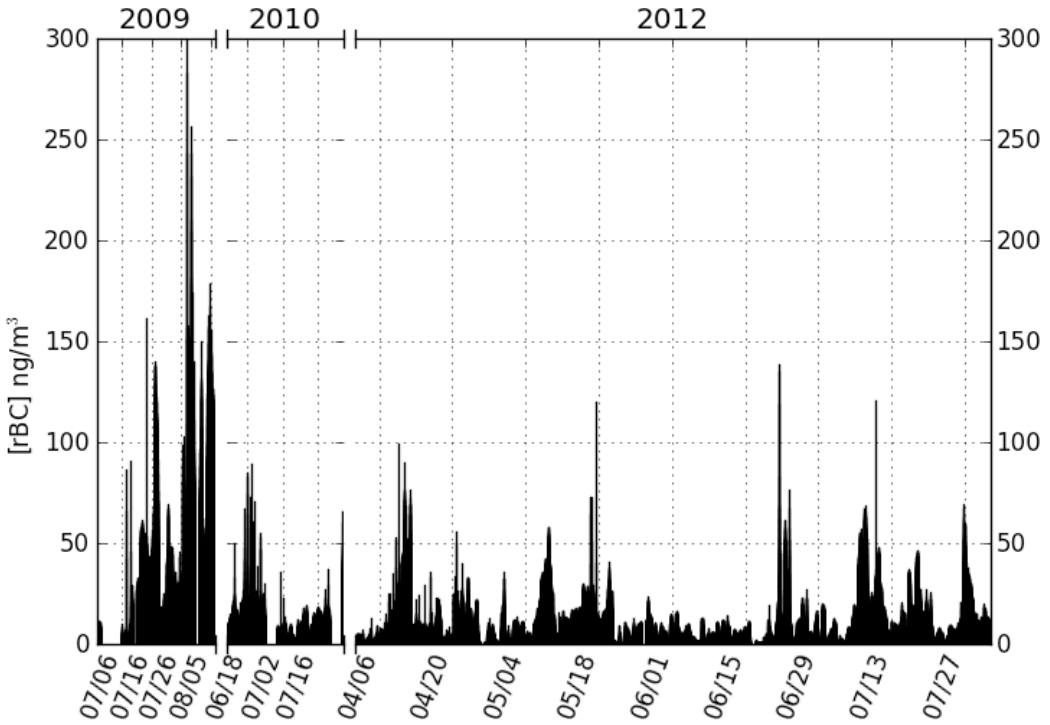

Figure 3. A time series of rBC mass concentrations for June 27 2009 - July 31, 2012. The data for 2012 and 2010 has been binned into 10 minute intervals. The data for 2009 has been binned in 15 minute intervals. Measurements impacted by local contamination have been removed.

Figure 4 shows a frequency distribution for the mass concentration data in Figure 3. This shows the same overall pattern as the frequency distribution for the 2012 mass concentrations (Figure 2) with most of the mass concentration occurring below 25 ng/m^3. However there are significant occurrences of mass concentrations over 50 ng/m^3 most of which are attributable to the biomass burning periods in the 2009 dataset.

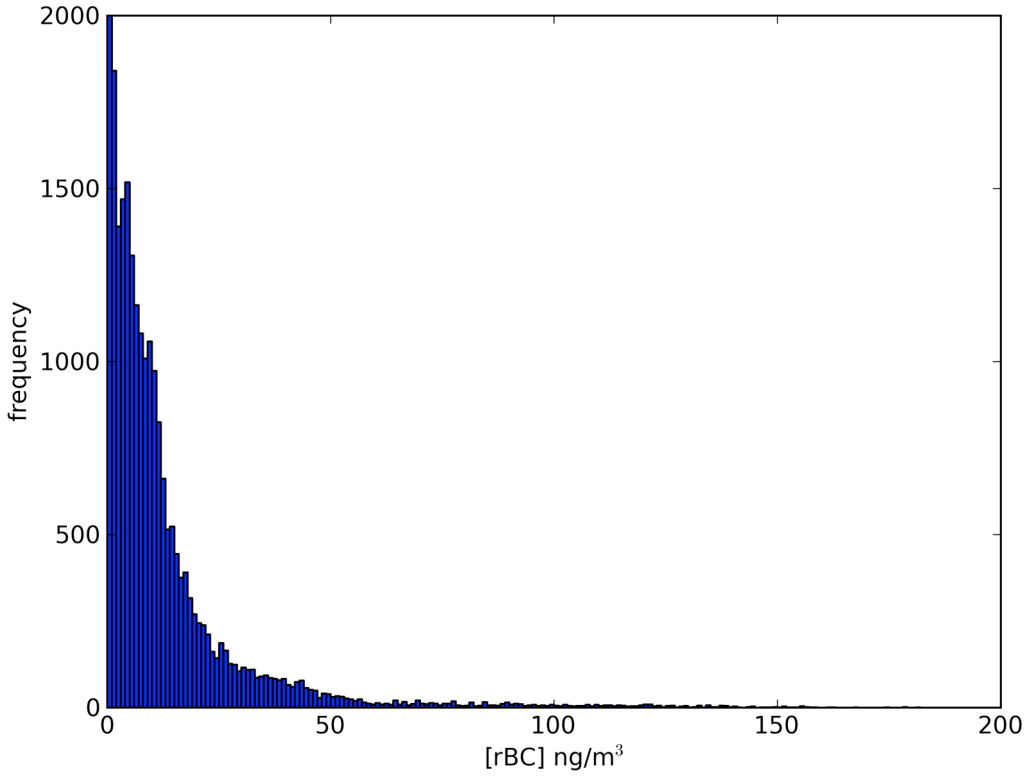

Figure 4. Frequency distribution for the rBC mass concentration data shown in Figure 3.

Appendix 3: *Do mixed source emissions from Asia influence black carbon concentrations at the Whistler high elevation site?*

Introduction:

Over the past several decades a wide variety of studies have shown that there is significant transport of both gas-phase and particulate pollutants across the Pacific from East Asia to Western North America (e.g. Jaffe, et al., 2003 and Leaitch, et al., 2009 and references therein). Intercontinental transport of pollutants has important implications for both global climate and local air quality, and it may significantly impact the ability of local jurisdictions to meet air quality standards.

To provide an initial assessment of the influence of long range transport from Asia to British Columbia on background levels of black carbon, we have focused on measurements carried out during the month of April, 2012. April was chosen since it is well known that during the spring-time transport from Asia has the highest frequency. In addition, for all the measurements carried out at Whistler so far, April should have the lowest impact from the boundary layer. We have also focused on measurements during the night (2000 to 0800 PST) since during the night, and in the spring, influence from the boundary layer should be minimal.

Experimental:

Back-trajectory analyses
To ascertain when air masses from Asia were reaching the Whistler high elevation site 12-day back trajectories were run every two hours for each night (2000 to 0800 PST) in April, 2012 using the NOAA-HYSPLIT model (Draxler & Rolph, 2012; Rolph, 2012). For the trajectory calculations the NCEP's GDAS global meteorological dataset was used. This has a time resolution of 3h and a horizontal resolution of 1º x 1 º. Each 12-day back trajectory was calculated at the elevation of Whistler peak as well as at 200m above and below the peak to help account for uncertainties in the initial conditions.

Results:

Back trajectory analysis showed air masses from Asia reaching the Whistler site during the nights of April 2- 3 from 2200hrs to 0600hrs, April 18 from 0400hrs to 0800hr, April 19 from 0000hrs to 0400hrs, and April 19-20 from 2000hrs to 0000hrs. A sample back-trajectory ending at 2300 hrs PST on April 3 is shown in Figure 5 and illustrates an air mass transported aloft across the northern Pacific Ocean.

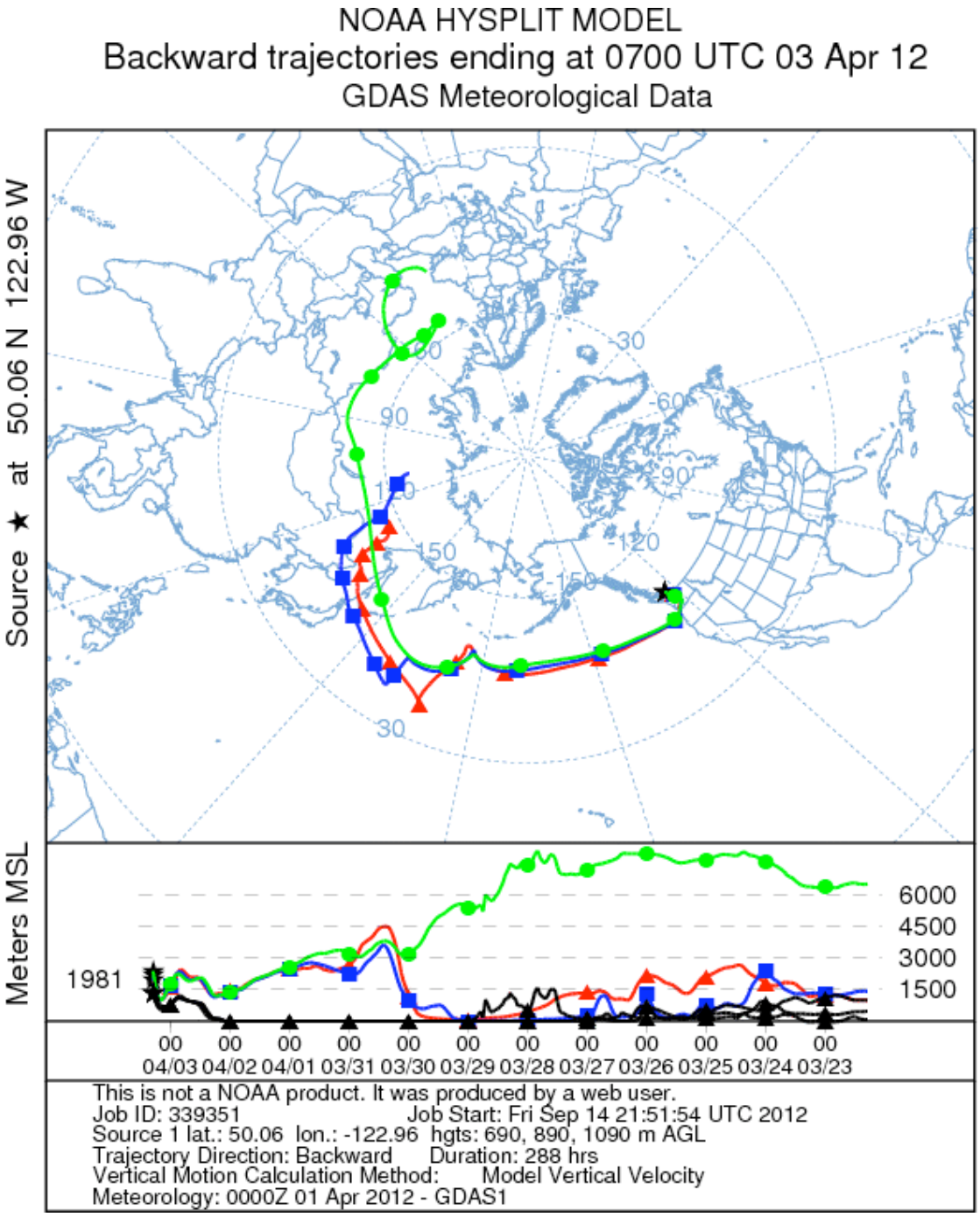

Figure 5. A 12-day back trajectory ending at 2300 hrs local time (PST) on April 3, 2012. The red trace is 200m below Whistler Peak, the blue trace is at Whistler Peak (2182m a.s.l) and the green trace is 200m above Whistler Peak.

Figure 6 shows the frequency distribution of rBC mass concentration for the times when back-trajectory analysis showed transport of air masses from Asia. The values range from 0.2 to 6.6 ng/m^3 with the majority of concentrations falling below 2 ng/m^3. These concentrations are relatively small compared to values observed at other times. However, preliminary results presented in Appendix IV suggest that the amount of black carbon transported to Whistler from Asia may sometimes be much higher, for example during biomass burning events.

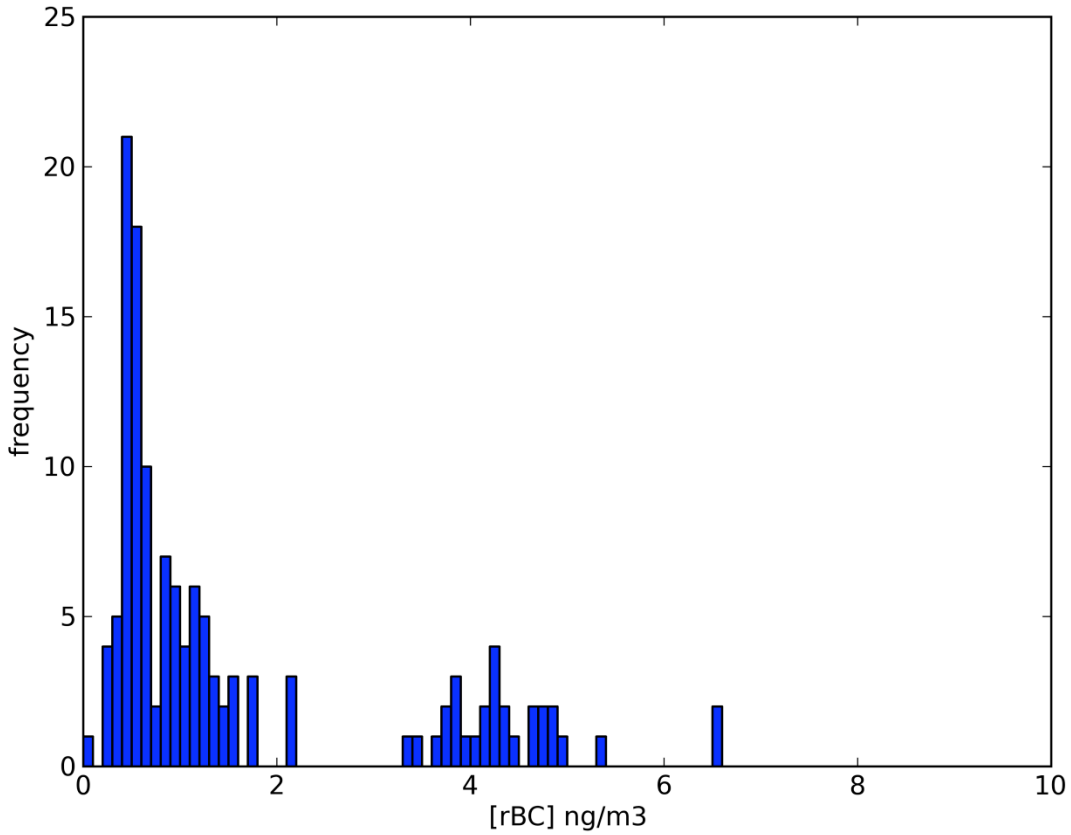

Figure 6. The frequency distribution of rBC mass concentration for the nights of April 2- 3 from 2200hrs to 0600hrs, April 18 from 0400hrs to 0800hr, April 19 from 0000hrs to 0400hrs, and April 19-20 from 2000hrs to 0000hrs. These times are when back trajectory analysis showed transport from Asia.

Appendix 4: *Long-range transport of black carbon from biomass burning in Siberia: Preliminary results.*

During July, 2012, Whistler and other parts of British Columbia were impacted by long range transport of forest fire plumes from Siberia (Ian McKendry, Paul Cottle, Richard Leaitch, Anne Marie Macdonald, Roxanne Vingarzan, private communications). The SP2 measurements suggest that these long range transport events of biomass burning plumes had a major impact on black carbon concentrations measured at Whistler. Figure 7 shows black carbon mass and number concentrations measured during this time period. Of interest are two periods (July 7-8 and July 10-11) where an increase in the rBC mass occurs without a correlated increase in the rBC particle number. This could arise from either particle ageing by coagulation or a change in the source (either location or type of fire, for example, this could be due to a change in the fire from flaming to smoldering). We are now looking at this event in more detail for a future publication with Environment Canada (Roxanne Vingarzan, private communications).

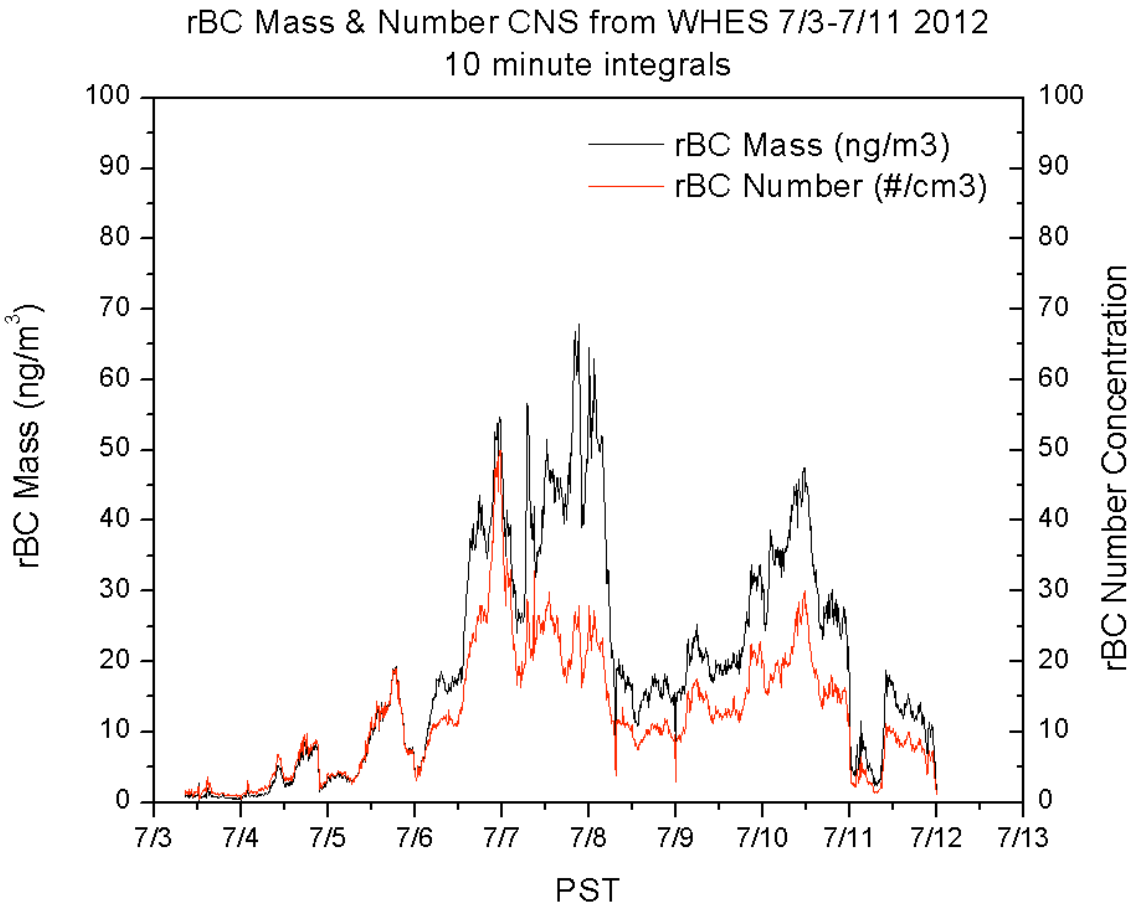

Figure 7. rBC mass and number concentrations for July 3 through July 13, 2012. During this period measurements may have been impacted by long-range transport of black carbon from biomass burning in Siberia**.**

Appendix 5: *Summary of results.*

Table 1 gives a summary of the mass concentrations of refractory black carbon measured at the Whistler high elevation site from 2009 to 2012. Also included for reference are other measured values for the mean tropospheric background and for biomass burning plumes.

Liu et al. (2010) measured the mass concentration of black carbon particles using an SP2 at the Jungfraujoch research station in Switzerland which sits at 3580 m a.s.l and, like Whistler, is often above the planetary boundary layer. They measured an average BC mass concentration for the free troposphere of 13 ± 5 ng/m^3, which is similar in magnitude to much of the Whistler data.

Sahu et al. (2012) used an SP2 to measure black carbon concentrations in four biomass burning plumes encountered on three flights during the ARCTAS 2008 campaign. Measured average BC mass concentrations ranged from 279 to 676 ng/m^3 for the four plumes, with an overall mean value of 513 ± 153 ng/m^3. These values are somewhat higher than the levels measured at Whistler during biomass burning events, but this may be a result of the large number of fires in California during the ARCTAS campaign and the proximity of these fires to some of the flight tracks.

Table 1. Summary of black carbon mass concentrations measured at the Whistler high elevation site from 2009 to 2012. Also included for reference are free tropospheric refractory BC mass concentration measured at Jungfraujoch, Switzerland (Liu et al., 2010) and the average refractory BC mass concentration from four biomass burning plumes in California (Sahu et al., 2012)

Dataset	Minimum (ng/m^3)	Maximum (ng/m^3)	Mean (ng/m^3)
2012 all data (Appendix 1)	0.01	139.0	9.6
2009 – 2012 all data (Appendix 2)	0.01	300.5	13.0
2009 and 2010 biomass burning events (3 events) (BC-Clear Report 1)	4.4	300.5	61.8
Asian transport epsiodes in April 2012 (Appendix 3)	0.24	6.59	1.6
Background (Liu et al., 2010)	13 ± 5 ng/m^3 (mean free tropospheric background)		
Biomass burning (Sahu et al., 2012)	513 ± 153 ng/m^3 (mean of four biomass burning plumes)		

Also available for comparison to the Whistler data are measurements from two sampling stations in the lower Fraser Valley (LFV). For these measurements particles were collected on filters and the light absorption due to black carbon was measured. The black carbon

mass concentrations measured at the LFV sites were more than an order of magnitude greater than the mass concentrations measured at the Whistler high elevation site (Table 1 and Table 2). These differences may be due in part to the difference in sampling techniques (i.e. the SP2 measures refractory black carbon while the filter based techniques measure all absorption at a given wavelength or wavelengths). In addition the LFV sites will be much more heavily influenced by local sources than will the remote Whistler site. A comparison of the SP2 and aethelometer in these local sites would be very interesting.

Table 2. Black Carbon Measurements from Burnaby South and Abbotsford in the LFV of BC.

Station	Minimum (ng/m^3)	Maximum (ng/m^3)	Mean (ng/m^3)
Burnaby South T18(1)	0	2422	764
Burnaby South T18 (2)	154	2600	478
Abbotsford T34 (1)	0	5536	636
Abbotsford T34 (2)	50	1492	539

(1) NAPS Partisol speciation sampler measurements; PM2.5 size cut, 24 hr samples one in 3 days (2003-2008) (Environment Canada NAPS)

(2)Magee Scientific aethelometer measurements 880 nm**;** For Burnaby South: Sept 2010 to Sept 2011, for Abbotsford: April 2009 to April 2010. (Environment Canada, Pacific and Yukon Region)

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