J2.20 URBAN AND REGIONAL AIR QUALITY MODELLING IN THE PACIFIC NORTHWEST

Xin Qiu*, Mike Lepage, J. Wayne Boulton, and Martin Gauthier
RWDI West Inc.
650 Woodlawn Rd. West
Guelph, Ontario, Canada, N1K 1B8

Colin di Cenzo
Environment Canada, Pacific & Yukon Region
#201 - 401 Burrard Street
Vancouver, British Columbia, Canada, V6P 6H9

1. INTRODUCTION

Megacities, like the Greater Vancouver Regional District (GVRD), Seattle, and Portland in the Pacific Northwest, can greatly influence the regional as well as the local air quality (RWDI, 2003). Studying this type of air quality problem is complicated at best and requires the consideration of local meteorological and synoptic conditions, effects of complex terrain, urban emission sources, and marine influences.

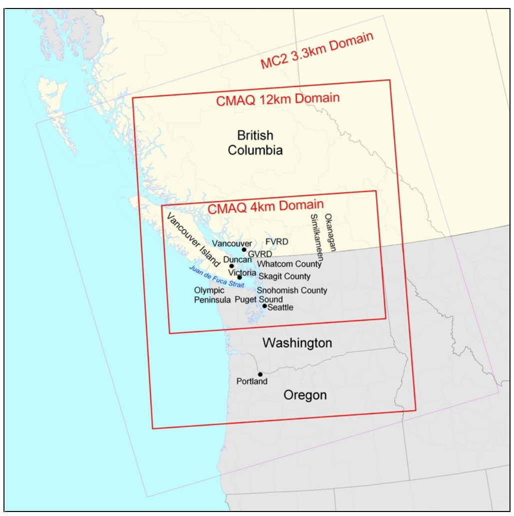

Figure 1. Study area and model domains

Environment Canada and RWDI West Inc., in collaboration with the University of British Columbia and other government agencies and institutions, conducted a project to investigate the impacts of Canadian and U.S. emissions from urban/industrial areas on ozone and PM2.5 within the Pacific Northwest region of Canada and the U.S. This project involved: the preparation of MC2 meteorological data for input into the SMOKE emission processing system and CMAQ air quality model, the compilation and processing of emission inventory data through SMOKE, and performing regional air quality modelling with CMAQ (di Cenzo and Lepage, 2003).

Modelling was performed over 12-km and 4-km nested domains as shown in figure 1. The Strait of Georgia, not indicated in the figure, lies between southern Vancouver Island and mainland British Columbia. The lower Fraser valley, also not indicated, stretches from Vancouver to the FVRD. Two meteorological episodes (one summer and one winter) and various trans-boundary and future year emission projection scenarios were simulated.

The summer period selected was August 09-20, 2001. This period was characterized by a dry blocking weather pattern with two regimes: a stagnant phase, and a well-mixed phase. This period coincided with the Pacific 2001 Field Study from which there was a rich meteorological and chemical dataset with which to perform model evaluations. The winter period selected was December 01-13, 2002. This period was characterized by a short stagnant phase, followed by a weak blocking pattern, and ended with a transient, well-mixed phase (Snyder, 2002). Details of the winter simulation are not discussed in this paper but are documented elsewhere (RWDI, 2003).

2. MC2 TO MM5 CONVERTER

One of the key developments made during the completion of this project was the creation of an MC2 to MM5 Converter. This utility converts MC2 meteorological modelling output into a pseudo-MM5 format. The purpose was to allow MC2 data to be processed through MCIP and used to drive both SMOKE and CMAQ, where MCIP is a meteorological interface program between MM5 and SMOKE/CMAQ (Byun and Ching, 1999). MC2 is a mesoscale meteorological model originally developed by Recherche Prévision Numérique (RPN), and used by Environment Canada, universities and other research institutions in Canada and Europe. This study represents the first time that MC2-generated meteorological fields have been incorporated into SMOKE and CMAQ (Boulton, et al., 2003).

The MC2 model runs were performed experimentally as high-resolution, operational forecasts at the University of British Columbia (UBC), Vancouver, Canada. MC2 was run on a Polar Stereographic

* *Corresponding author*: Xin Qiu, RWDI West Inc., 650 Woodlawn Rd. W., Guelph, Ontario, Canada, N1K 1B8, email:xq@rwdi.com

projection with a grid spacing of 3.3-km over an expanded model domain (307 x 357 horizontal grids) and 38 pressure levels in RPN standard format.

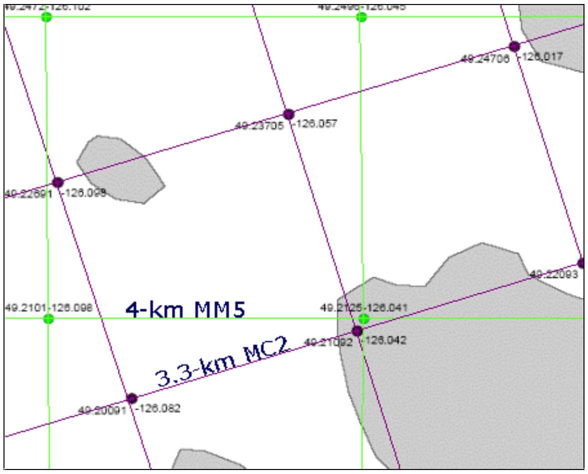

Figure 2. Interpolation between projections and grid resolutions

These MC2 outputs were interpolated to the 12-km or 4-km grid spacing based on the corresponding grid coordinates in Latitude and Longitude coordinates. For the horizontal grids, inverse-squared distance weighting was applied to interpolate the MC2 data onto the new, uniformly spaced MM5 grid in Lambert Conic Conformal projection (Figure 2). For vertical layers, the 38 pressure levels (mbar) from MC2 were converted and then aggregated down to 30 sigma levels in MM5 format using an inverse-squared distance weighting function.

The meteorological variables used in MC2 are not the same as those adopted in MM5. Therefore, the conversion utility also had to include functions to map and recalculate meteorological variables from MC2 to MM5. The mapping process was performed with additional input from NCAR and members of the US EPA responsible for the development of MCIP. The primary focus of this effort was to map or recalculate the necessary meteorological parameters required by CMAQ. The cross-reference table has been reproduced in Table 1.

The 3-D meteorological fields were then exported in MM5 binary format. Run-scripts were also developed to execute the program and process the hourly MC2 data automatically for an entire episode. The conversion of the MC2 wind and temperature fields to MM5 format was evaluated by comparing the original MC2 data and the conversion results, as well as to observation data. The evaluation indicated that both large and small scale wind flow patterns in MC2 were replicated in the resultant MM5 format output. Vertical profiles of wind and temperature matched very well. Although there is room for improvement as it pertains to maintaining mass conservation, the conversion results were considered adequate for air quality modelling purposes and the MM5 wind fields produced in this manner performed very well in both SMOKE and CMAQ.

Table 1. MC2 to MM5 parameter mappings

Time Invariant							
MCIP Parameter	**MM5 Parameter**	**MM5 Units**	**Dimensions**	**MC2**	**MC2 Units**	**Dimension**	**Notes**
ALBEDO	ALBD	%	(land,2)	AL	fraction	(land,2)	
EMISS	SFEM	fraction	(land,2)	Manually input		(land,2)	
LANDUSE	LAND USE	category	(I,J)	Manually input – converted from MC2 to MCIP landuse codes			Cross
LATCRS	LATITCRS	decimal degrees	(I,J)	LA	decimal degrees	(I,J)	
LONCRS	LONGICRS	decimal degrees	(I,J)	LO	decimal degrees	(I,J)	
MAPCRS	MAPFACCR	[1]	(I,J)	Manually input – MCIP map projection			Cross-point
MAPDOT	MAPFACDT	[1]	(I,J)	Manually input – MCIP map projection			Dot-point
MAVAIL	SLMO	fraction	(land,2)	HS	fraction	(land,2)	
SIGMAH	SIGMAH	half-sigma	(K)	SL	half-sigma	(K)	
TERRAIN	TERRAIN	M	(I,J)	ME	M	(I,J)	Cross-point
ZNT	SFZ0	Cm	(land,2)	ZP	LOG (m)	(land,2)	
Time Variant							
MCIP Parameter	**MM5 Parameter**	**MM5 Units**	**Dimensions**	**MC2**	**MC2 Units**	**Dimension**	**Notes**
GLW	LWDOWN	W/m^2	(I,J)	SI	W/m^2	(I,J)	= -LWDOWN
GROUNDT	GROUND T	K	(I,J)	TS	K	(I,J,3)	Take the first one from MC2
HFX	SHFLUX	W/m^2	(I,J)	Manually converted from MC2 to MCIP sensible heat flux			
PP	PP	Pa	(I,J,K)	QX	Pa	(I,J,K)	Interpolate to Sigma before interpolating to MM5
PSA	PSTARCRS	Pa	(I,J)	2P – PZ	Pa	(I,J)	
QCA	CLW	kg/kg	(I,J,K)	QD	kg/kg	(I,J,K)	Interpolate to Sigma before interpolating to MM5
QFX	LHFLUX	W/m^2	(I,J)	Manually converted from MC2 to MCIP latent heat flux			
QIA	ICE	kg/kg	(I,J,K)	QE	kg/kg	(I,J,K)	Interpolate to Sigma before interpolating to MM5
QRA	RNW	kg/kg	(I,J,K)	RQ	kg/kg	(I,J,K)	Interpolate to Sigma before interpolating to MM5
QSA	SNOW	kg/kg	(I,J,K)	= 0	kg/kg	(I,J,K)	Interpolate to Sigma before interpolating to MM5
QVA	Q	kg/kg	(I,J,K)	HU	kg/kg	(I,J,K)	Interpolate to Sigma before interpolating to MM5
RAINCON	RAIN CON	Cm	(I,J)	PC	M	(I,J)	
RAINNON	RAIN NON	Cm	(I,J)	PR - PC	M	(I,J)	
REGIME	REGIME	[1]	(I,J)	Manually converted from MC2 to MCIP stability classes			
RGRND	SWDOWN	W/m^2	(I,J)	FU	W/m^2	(I,J)	
TA	T	K	(I,J,K)	TT	C°	(I,J,K)	Interpolate to Sigma before interpolating to MM5
UA	U	m/s	(I,J,K)	UU	Knots	(I,J,K)	Interpolate to Sigma before interpolating to MM5
UST	UST	m/s	(I,J)	UE	m/s	(I,J)	
VA	V	m/s	(I,J,K)	VV	Knots	(I,J,K)	Interpolate to Sigma before interpolating to MM5
WA	W	m/s	(I,J,K+1)	WZ	m/s	(I,J,K)	Let K+1 layer equal the K layer (Interpolate to Sigma)
ZPBL	PBL HGT	M	(I,J)	H	M	(I,J)	

3. CMAQ MODELLING FOR AUGUST 2001

The Pacific 2001 Field Study, an intensive field monitoring programme carried out by a number of researchers from Canadian and U.S. government and academic institutions, began on August 13, 2001 during a stable blocking weather pattern over the southern coast of British Columbia. Over the next two weeks, the weather affecting the project was comprised of three regimes: a dry stable blocking pattern; a wet period; and finally a transient period (Snyder, 2002). The dry weather (blocking pattern) lasted until August 20, allowing pollutant levels to elevate, reaching their peak on August 16 during the stagnant phase.

The synoptic pattern during the dry period can be subdivided into two phases: a stagnant phase and a well-mixed phase. Based on the meteorological analysis done by Snyder (2002), the stagnant phase (August 10 to 15) could be described as typical of ozone episodes in this region. The well-mixed phase, however, showed ozone and PM concentrations declining as a result of increased mixing heights and an incursion of marine cloud into the region. The wet period that followed started on August 21 and was associated with an intense low-pressure system moving south into the Gulf of Alaska. An unsettled (transient) period began after the four days of rain and persisted throughout the remainder of the Pacific 2001 experiment. There was virtually no rain during this latter period due to the controlling effect of the long wave ridge east of the region with only minor troughs and ridges moving across the south coast.

The highest pollutant concentrations occurred during the August 10 to 15 stagnant phase. The study period for the CMAQ modelling was selected to encompass the portion of the stagnant phase that was included in the Pacific 2001 field study (i.e., August 13 to 15), and was extended to also include the well-mixed phase (August 15 to 20). In addition to the actual model run period, model spin-up time was required to allow the simulated atmosphere to evolve and arrive at a state of chemical maturity. For these reasons, the actual CMAQ model period for the 12-km domain extended from 1300 UTC on August 9 to 1300 UTC August 20. The period for the 4-km domain also started at 1300 UTC on August 9 and ended five hours earlier than the 12-km domain, at 0800 UTC on August 20.

4. MODEL EVALUATION AND DATA ANAYLYSIS

4.1 Ozone

A total of eight monitoring stations (six in Canada and two in the U.S.) were selected to evaluate the model performance for ozone. The following discussion is based on the results for the Vancouver International Airport station. Figure 3 depicts the model performance (4 km run) for ozone (left upper corner graph) relative to the available monitoring data. This monitoring station is located near Vancouver International Airport situated on the land / sea interface and is the westernmost station used in the ozone analysis. The observed ozone levels at this site were generally below 40 ppb throughout the simulation period, but climbed to about 60 ppb on days four and five (August 12 and 13, 2001).

The CMAQ simulation performed well in terms of the replication of diurnal patterns of ozone levels for both the 12-km and 4-km domains. On days four and five (August 12 and 13), the daytime peaks were underestimated by about 15% and 30%, respectively. On the last four days of the simulation (August 16 through 19, i.e., the well-mixed period) and on the first day (a spin-up day), the daytime peaks were overestimated by 20 to 40%. On the first day and also the last 2 days of the simulation, the nighttime minimum ozone level was overestimated at the 12-km grid-spacing (not shown). This problem was rectified at the 4-km grid spacing. On the remaining days (August 11, 12, 15 and 16) the predicted daytime peaks and nighttime minimums were very close to the observed values. In general, the 4-km grid spacing resulted in better predictions of nighttime minimum ozone levels at Vancouver Airport but did not lead to an improved prediction of the daytime peaks.

Analyses (di Cenzo and Lepage, 2003; Boulton et al., 2003; RWDI, 2003) have indicated that diurnal fluctuations in the modelled ozone levels show highest concentrations occurring in the late afternoon and lowest concentrations around midnight. Larger magnitude fluctuations tend to occur near the larger NO_X sources (e.g, urban and marine emission areas of Vancouver and Portland), with smaller fluctuations found inland in the mountainous and rural areas.

4.2 $PM_{2.5}$

Both the 12-km and 4-km CMAQ model results for $PM_{2.5}$ show less short-term fluctuations in concentration but more pronounced diurnal variability than that was actually measured (Figure 3, lower right corner). The overall result of this is a slight overestimate of $PM_{2.5}$ levels at night and underestimate during the day. However, a comparison of the daily-average $PM_{2.5}$ levels indicates good agreement between the modelled and observed for both domains. Therefore, although the model does not appear to do a particularly good job of replicating the short-term highs and lows in the $PM_{2.5}$ fluctuations, the overall prediction of $PM_{2.5}$ mass over the course of a day is quite good. Overall, there are few differences between the 12-km and 4-km CMAQ results.

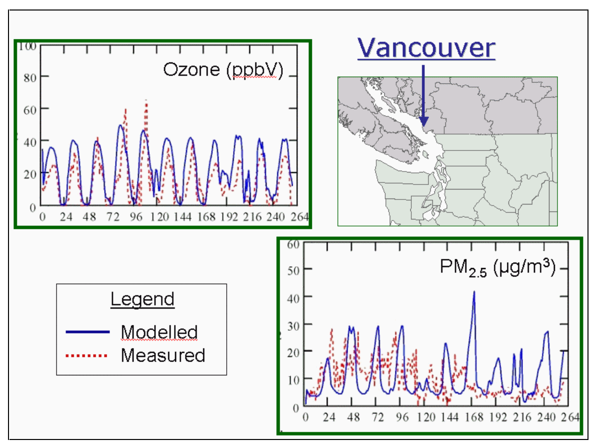

Figure 3 Comparison between CMAQ model output and measurement at Vancouver International Airport

The observed PM data showed considerable diurnal variation and that many of the peaks occurred one or two hours after sunrise (Snyder, 2002). Overall, $PM_{2.5}$ values peaked between August 11 and 13 (Figure 3). CMAQ captured the major pattern of the variation of the $PM_{2.5}$ levels, but missed some details in between.

The model evaluation indicated that using high-resolution MC2 model outputs to drive SMOKE and CMAQ resulted in good overall model performance on both grid definitions.

4.3 Sea Breeze, Mountain/Valley Flows and CMAQ Simulations

Based on the analysis of air quality and meteorological monitoring data, Snyder (2002) and McKendry (2000) suggested that during the summer, different meteorological forcings on a diurnal scale, play an important role on the resultant temporal and spatial patterns of O_3 and $PM_{2.5}$ in this region. Several factors, including the effects of blocking ridges, subsidence inversions, light winds and high temperatures in combination with sea breeze and mountain flows are believed to result in elevated levels of PM as well as O_3 in the GVRD/FVRD area.

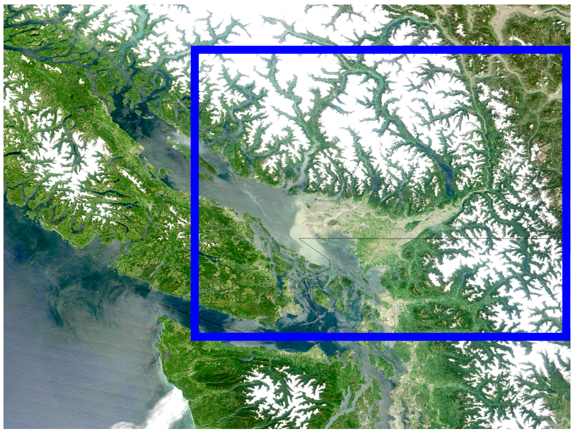

Figure 4. High-resolution GIS image of the Lower Fraser Valley area. The black thin line indicates the US-Canada border

Figure 4 is a 250m resolution satellite image of the Lower Fraser Valley and surrounding area. The blue box outlines a subset of the 4 km CMAQ domain. Figure 5 presents the surface wind field overlaid onto the modelled O_3 concentrations for August 12, 2300 UTC (top) and August 13, 1300 UTC (bottom).

In general, ozone concentrations build up during the day around and slightly downwind of the urbanized areas of the Greater Vancouver Regional District (GVRD). A sea breeze and onshore westerly flow push the urban ozone precursors downwind toward the east away from the urban and marine areas (uppermost plot).

In contrast, a land breeze and mountain drainage flows from the northeast along the lower Fraser valley push the pollutants back toward the west during the night (bottom plot). At the same time, ozone is depleted through titration with residual oxides of nitrogen (NO_X) and by deposition processes. In the GVRD urban area, high concentrations of NO_X results in O_3 levels that are very low (near zero) throughout the night. Similar features can be seen near the southeast coast of Vancouver Island where high levels of NOx emissions from ferries and marine vessels running between Tsawwassen and Nanaimo titrate the ozone at night. This day-night cycle persists throughout the stagnant phase, causing ozone in the vicinity of the Canada/U.S. border to slosh back and forth in a short-range, east-west fashion until an incursion of marine cloud and a stronger inflow from the Pacific Ocean (the start of the well-mixed phase) affected the region.

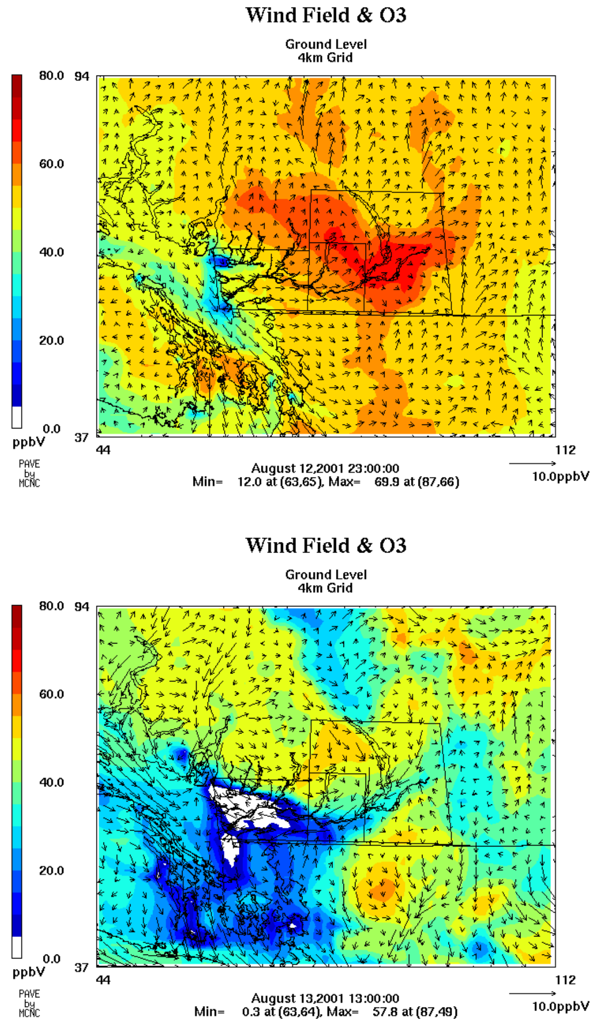

Figure 5. Modelled O_3 concentrations (ppb) and wind field for August 12, 2300 UTC (top) and August 13, 1300 UTC (bottom)

$PM_{2.5}$ also starts by building up near the major primary sources (urban/industrial/marine areas) as shown in Figure 6 (top). In a similar manner to the ozone simulations, the combination of sea breeze and an onshore westerly flow pushes the $PM_{2.5}$ concentrations inland, toward the east and away from the urban and marine areas during the daytime. However, mountain flows from the northeast along the Fraser Valley push the pollutants back toward the west during the night, causing $PM_{2.5}$ levels to increase in the GVRD (bottom-most plot). This influx of $PM_{2.5}$ caused by the mountain flow brings polluted air back into the emission source region, resulting in a net increase in $PM_{2.5}$ levels at night.

Although there is a day-night cyclic pattern in the $PM_{2.5}$, it is very different than the one seen for ozone. When the ozone-rich airmass moves back into the high

NO_X emission source region at night (GVRD), ambient O_3 levels go down due to titration. $PM_{2.5}$ on the other hand, does not get destroyed in this manner, but rather accumulates over the urban area due to primary $PM_{2.5}$ emissions and the formation of secondary PM species at night. Therefore, although the daily sloshing of the airmass up and down the valley results in a very distinct diurnal pattern (formation and destruction) of O_3, high $PM_{2.5}$ levels tend to travel up and down the valley and accumulate over time (figure 6 – bottom panel).

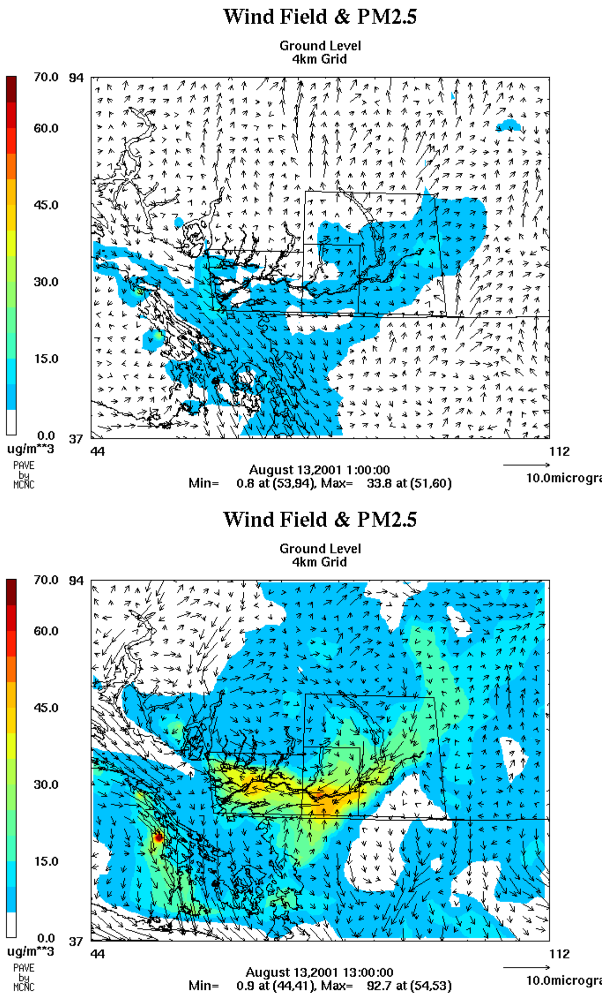

Figure 6. Modelled $PM_{2.5}$ concentrations (ppb) and wind field for August 13, 0100 UTC (top) and August 13, 1300 UTC (bottom)

This phenomenon is fairly unique to this region and is dissimilar to most other regions of Canada and the U.S. where there is often a positive correlation between ozone and $PM_{2.5}$ levels over both space and time. The results from this study are supported by the findings of other researchers (e.g., McKendary, 1999).

In short, daytime air parcels affecting the lower mainland originated from the northwest and travelled through the inner Straits. Local scale forcing (sea breeze) steered the air eastward up the valley. At night, an opposite air movement (mountain flow) dominated over the GVRD/FVRD. Ozone and $PM_{2.5}$ concentrations are significantly influenced by these meteorological factors. The results of the MC2/CMAQ modelling support the findings of Snyder (2002).

5. CONCLUSIONS

This paper presents brief summary of some of the findings from a study focused on preparing a regional modelling environment that can be used to evaluate the impacts of Canadian and U.S. emissions, from man-made and natural sources, on ozone (O_3), fine particulate matter ($PM_{2.5}$) and visibility within the Pacific Northwest. The study involved: the preparation and conversion of MC2 meteorological data for input into SMOKE and CMAQ, the compilation and processing of emission inventory data, and air quality modelling over nested 12 and 4-km grid resolution domains for two meteorological episodes (summer 2001 and winter 2002).

The model evaluation indicated that using high-resolution MC2 model outputs to drive SMOKE and CMAQ resulted in good model performance on both grid definitions. Results from the summer scenario runs indicate that urban emissions, including those from marine, mobile and industrial activities, have a significant impact on both local and downwind O_3 and $PM_{2.5}$ levels. Modelling results also indicate that not only regional / synoptic weather patterns, but also localized sea breeze and terrain effects influence the trans-boundary movement of pollutants in this region, although for the episodes modelled, short range transport phenomena occur more frequently than long-range transport. As shown through a more detailed look at the complex nature of the formation and transport of secondary pollutants, sea breeze and mountain flows play a very important, yet different, role on both O_3 and $PM_{2.5}$ patterns in the Lower Fraser Valley.

References:

Boulton, J. W., M. Lepage, X. Qiu, M. Gauthier, and C. di Cenzo, 2003: New Developments and Applications of Models-3 in Canada. *2003 Models-3 User's Workshop*, Research Triangle Park, NC

di Cenzo, C. and M. Lepage, 2003: The Application of CMAQ over the Pacific Northwest to Determine the Significance of the International Trans-Boundary Flows of Air Contaminants. 2003 *Models-3 User's Workshop*, Research Triangle Park, NC

McKendry, I.G., 1999: PM10 Levels in the Lower Fraser Valley, B.C., Canada: An overview of spatio-temporal variations and meteorological controls, *J. Air and Waste Manag. Assoc.* **50**, 443-452.

RWDI 2003: Pacific Northwest International Air Quality Modelling Project, Phase 1 Report, Environment Canada – Pacific & Yukon Region

Snyder, B., 2002: Meteorological Summary of the Pacific 2001 Air Quality Field Study. *Environ. Can. Report EC/GB 02-064*