APPLICATION OF CMAQ OVER THE PACIFIC NORTHWEST TO DETERMINE THE SIGNIFICANCE OF THE INTERNATIONAL TRANS-BOUNDARY FLOWS OF AIR CONTAMINANTS

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1.0 INTRODUCTION

Since the 2002 Models-3 Workshop, Environment Canada and RWDI West Inc. assembled a CMAQ modelling system for the Pacific Northwest (RWDI, 2003a).

CMAQ was set up and validated over a domain that straddled 525 kilometers each side of the British Columbia - Washington border, see Figure 1. The June 2001 version of CMAQ, parallelised for a PC/Linux cluster running Redhat Linux v7.3, was used. The photochemical mechanism was the ‘radm2_ae2_aq’.

Figure 1. Geographical references and domain extents. 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.

The simulations were performed for a typical summer period and for a typical winter period. The summer period selected was August 09-20, 2001. This period embraced a dry blocking weather pattern of 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. The winter period selected was December 01-13, 2002. This period comprised a short stagnant phase, followed by a weak blocking pattern, and ended with a transient, well-mixed phase.

The emissions model selected to provide CMAQ with the required temporal, spatial, and speciation data was SMOKE, version 1.3. To the extent possible, the base year for emissions data was 2000. Generally, 2000 data were only available for the 4-km domain; elsewhere, and where unavailable, 1995 data grown to the year 2000 were used. These generalisations are complicated by the fact that the major inventoried years in Canada were 1995 and 2000, and in the U.S.A. were 1996, 1999, and 2002. American data for 1996 were used alongside Canadian data for 1995. American data for 2002 were used alongside Canadian data for 2000, and where 2002 data were unavailable, 1999 data were used. Wildfire emissions were not used.

Point, area, mobile (including marine), and biogenic emissions datasets were assembled for both the summer and winter periods. Emissions data were prepared at 4-km resolution. For the CMAQ simulations carried out at 12-km resolution, the emissions data were simply aggregated upwards.

Two emission scenarios were constructed from the basecase emissions. In the first, all U.S. anthropogenic sources were removed; in the second, all Canadian anthropogenic sources.

Both CMAQ and SMOKE were driven with meteorology from the Canadian Mesoscale Compressible Community Model (MC2) at a resolution of 3.3 km. For details, see Boulton (2003).

2.0 QUALITATIVE ANALYSIS OF SIMULATIONS FOR THE YEAR 2000 BASECASE

2.1 Summer ozone

In the 12-km grid domain, ozone concentrations build up during the day around and slightly downwind of the urbanized areas of the Greater Vancouver Regional District (GVRD), Seattle, and Portland. A sea breeze and onshore westerly flow push the urban ozone

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precursors downwind toward the east away from the urban and marine areas. In contrast, during the nighttime, a land breeze and mountain drainage flows from the northeast along the lower Fraser valley push the pollutants back toward the west. At the same time, ozone is depleted through titration with residual oxides of nitrogen (NOX) and by deposition processes. 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 an 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.

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 NOX sources such as urban areas and marine emission areas (e.g., Vancouver and Portland), with smaller fluctuations found inland in the mountainous and rural areas.

The overall patterns and trends in the 12-km simulation are also seen in the 4-km results. One difference between the two is the improvement over coastal areas of the resolution of the temporal and spatial fluctuations of ozone concentrations. For example, marine emissions appear to contribute to higher ozone levels during the day and lower ozone levels night in the coastal portion of the 4-km domain. Generally though, the overall results are fairly similar between the two simulations.

2.2 Winter ozone

Photochemical conditions in winter are not conducive to ozone formation. Winter ozone levels were found to be negligible. Thus, although modelled, no results for winter ozone are presented.

2.3 Summer PM2.5

In the 12-km grid domain, PM2.5 starts to build up in the vicinity of the major primary sources (urban/industrial/marine areas) after about 24 hours of model spin-up. In a similar manner to the ozone simulations, the combination of sea breeze and an onshore westerly flow pushes the PM2.5 concentrations inland, toward the east away from the urban and marine areas during the daytime. And, mountain flows from the northeast along the Fraser Valley push the pollutants back toward the west during the night. This day-night cyclic pattern in the PM2.5 levels also persists until the onset of the well-mixed phase.

In the 4-km simulations, results are similar but show somewhat improved definition of local hotspots near the sources of primary PM2.5 emissions. Additional details in the flow of PM2.5 resulting from valley flows and topographic effects are more noticeable.

2.4 Winter PM2.5

During the model spin-up and stagnant meteorological periods (December 01-07), PM2.5 levels build up around and slightly downwind (east) of the urbanized areas of the GVRD, Seattle, and Portland.

During the weak blocking period (December 07-10), offshore flows and land breeze effects push the urban plumes toward the west and over the Pacific Ocean. It is notable that during December 07-09, high concentrations of PM2.5, which originally formed in the Seattle area and over the GVRD, move north and westward toward Vancouver Island. This polluted airmass then spreads northwestward along the Strait of Georgia, westward along the Juan de Fuca Strait, and over the southern coast of Vancouver Island. The result was relatively high PM2.5 levels over southern Vancouver Island (e.g., Victoria, Duncan), the Strait of Georgia, and the coastal area of the GVRD. In contrast to the local-scale impacts, these impacts are more transboundary in nature.

December 10-13 is marked by a well-mixed phase with much stronger southerly and southwesterly wind flows that effectively purge the polluted airmass, resulting in significantly lower PM2.5 levels throughout the 12-km domain.

3.0 SIGNIFICANCE OF TRANSBOUNDARY TRANSPORT

The approach used to look at the significance of transboundary transport was to compare the ambient air concentrations of ozone and PM2.5 of the basecase situation (all emissions left on) with those that resulted when either all the Canadian anthropogenic emissions or all the American anthropogenic emissions were turned off (RWDI, 2003b).

The relationship between emissions and ambient air quality is not linear. For example, ozone results from a simulation involving all emission sources will not equal the sum of the results from Canada-only and US-only simulations. Nonetheless, these simulations do provide a reasonable indication of the relative impacts associated with transboundary pollutant transport.

3.1 Qualitative analysis of the simulations for the no-U.S. anthropogenic emissions scenario

Summer ozone

In the no-U.S. anthropogenic emissions scenario (NOUS), the simulation shows the expected absence of elevated ozone levels near the American urban centres. There is some ozone formation that does take place during the day throughout the American portion of the domain. This formation is attributed to emissions of volatile organic compounds (VOCs) and NOX from biogenic (natural/background) sources. Due to onshore westerly flows that dominate the coastal regions in the

U.S.A. and Canada during this episode, the NOUS ozone plumes that form over the GVRD, Fraser River Regional District (FVRD), and the Strait of Georgia (from marine emissions) move generally eastward along the Canada/U.S. border.

At 0000 UTC August 12, peak NOUS ozone levels (about 60 ppbV) in the GVRD and FVRD are lower by about 10 ppbV than what is seen with the U.S. emissions left on. This suggests that, under these meteorological conditions, U.S. emissions contribute to Canadian ozone precursors. In general, however, the impact of transboundary pollutant and precursor transport is short-ranged, limited to within tens of kilometers either side of the border.

On a number of occasions during August 11-14, ozone concentrations build up over Juan de Fuca Strait, around the southern tip of Vancouver Island, and over the GVRD before travelling southward across the northern tip of the Olympic Peninsula and Puget Sound. At other times, a northerly pulse of air pushes Canadian ozone plumes from southern B.C. (namely the FVRD, central Okanogan, and Okanogan-Similkameen regions) into northern Washington State (Whatcom, Skagit, and northern Snohomish Counties). This intrusion of polluted air is more transboundary in nature and can extend as far south as 100 km of the border. From August 17-20, because the major wind flows come from the southwest, there is no significant transport of ozone from Canada to the U.S.A.

Summer PM2.5

The NOUS simulation results for PM2.5 are similar to that for ozone. Biogenic and soil emissions of VOCs, NOX and ammonia (NH3) in the U.S.A. continue to contribute to the formation of PM2.5 over the U.S. portion of the domain. Due to the onshore westerly flows, the PM2.5 plumes formed over the GVRD/FVRD and the Strait of Georgia (from marine emissions) generally move eastward along the Canada/U.S. border. Peak NOUS PM2.5 levels in the GVRD from August 11-16 are lower (by about 14 µg/m3) than what is seen when the U.S. emissions are left on, which suggest that, under these meteorological conditions, American emissions contribute to precursors of Canadian PM2.5. However, this impact of transboundary pollutant transport is relatively short-ranged.

On several occasions, PM2.5 levels build up over Juan de Fuca Strait and around the southern tip of Vancouver Island before travelling southward over the northern tip of the Olympic Peninsula and Puget Sound. Marine emission sources and emissions from Victoria are thought to play the major role in this phenomenon. Emissions from the GVRD can also be seen to drift southward and impact northern Whatcom County.

Between 0400-1700 UTC on August 15, the same northerly pulse of air that pushed Canadian ozone plumes from southern B.C. into northern Washington State brings with it elevated levels of PM2.5, extending as far south as 100 km of the border. From August 17-20, because the major wind flows come from the southwest, there is no significant transport of PM2.5 from Canada to the U.S.A.

Winter PM2.5

The model results for the NOUS scenario show low PM2.5 levels in the U.S.A. compared to the basecase, except for on December 02-03 when easterly winds change to northerly winds for a period of time. During this period, the PM2.5 plume moves from GVRD/FVRD and Strait of Georgia to the northern tip of Olympic Peninsula and to Seattle. Other minor intrusions into the U.S.A. occur all along the valleys that line the Canada/U.S. border during these periods. In contrast, the NOUS PM2.5 levels over Vancouver Island are lower than the basecase, indicating that elevated PM2.5 levels from the U.S.A. typically travelled northward over Vancouver Island.

On the other days during this episode, there is little or no cross-boundary impact from Canada to the U.S.A. due to the predominantly easterly to southerly wind flows.

3.2 Qualitative Analysis of the Simulations for the No-Canadian Anthropogenic Emissions Scenario

Summer ozone

For the no-Canadian anthropogenic emissions scenario (NOCAN), the simulation shows the expected absence of elevated ozone levels near the Canadian urban centres. There is some ozone formation that takes place during the day throughout the Canadian portion of the domain due to emissions of VOCs and NOX compounds from biogenic sources. Due to onshore westerly flows that dominate the coastal regions in the U.S.A. and Canada during this episode, the NOCAN ozone plumes that form over the urban areas of Seattle and Portland move generally eastward, parallel to the Canada/U.S. border.

Some relatively weak, short-range transport of ozone and its precursors from the U.S.A. can be seen over the GVRD/FVRD and southern portions of the Strait of Georgia from August 11-15. For August 16-17, major wind flows come from southwest (from U.S.A. to Canada) and induce some limited but increased ozone levels. For example, peak NOCAN ozone levels in the FVRD are around 55 ppbV at 0000 UTC on August 17, which suggests that U.S. emissions contribute significantly to ozone precursors crossing the border. During the same period, peak NOCAN ozone levels in Seattle are slightly lower than what is shown for the basecase, which suggests that there is a lack of ozone precursors that are normally supplied from the Canadian side of the border, most likely from marine emission sources. From August 18-20, although major wind flows come from southwest (from the U.S.A. to Canada), the transboundary impacts on ozone levels are quite low because of fairly high wind speeds and subsequent ventilation.

Summer PM2.5

Overall, the PM2.5 results are similar to those for ozone. Due to the onshore westerly flow, the urban PM2.5 plumes over and downwind of Seattle and Portland move generally eastward, parallel to the Canada/U.S. border, resulting in relatively little transboundary transport into the GVRD/FVRD and the southern portion of the Strait of Georgia for a number of hours during the simulation. However, at other times (such as during the late afternoon of the last four to five days of the episode) PM2.5 levels in north-central Washington in the NOCAN simulation are much lower than the basecase results (about 15 to 20 µg/m3 lower). This suggests that a normally polluted airmass from the Canadian side of the border, likely associated with marine emissions, moves southward into the U.S.A.

Winter PM2.5

The NOCAN simulation results point to some unique transboundary phenomena. From December 01-05, easterly flows dominate the entire domain and the PM2.5 plumes formed over the Seattle and Portland regions move offshore to the west, over the Pacific Ocean. There are no significant transboundary impacts from the U.S.A. on Canada, except for the lower tip of Vancouver Island (e.g. Victoria) and the GVRD area.

However during December 06-10, the wind flow patterns veer to southeasterly, causing the PM2.5 plume from the Seattle region to move northwestward across the straits of Georgia and Juan de Fuca and over the southern coast of Vancouver Island. Compared to the basecase results, the PM2.5 concentrations from NOCAN simulations in these areas are quite high with peaks of around 24 µg/m3 (i.e., about 50 to 60% of basecase levels can be attributed to transport from the U.S.A.). There is relatively little evidence of transboundary transport elsewhere in the model domain.

During December 10-13, stronger southerly winds dominate the entire domain. Evidence of transboundary effects is less discernable and more localized, resulting in low PM2.5 levels throughout the domain.

4.0 SUMMARY AND CONCLUSIONS

The central Georgia Basin and the Puget Sound area, including the GVRD/FVRD, southern Vancouver Island, Whatcom County, and Seattle, are highly populated, commercialised, and industrialized, with intense transportation networks (road and marine). As such, emissions from this area are significantly higher than the rest of the 12-km model domain. And due to the topography of the GVRD/FVRD, transboundary impacts both from and to Canada and the U.S.A., depending on meteorological conditions, are not unusual.

Meteorological conditions in Georgia Basin and Puget Sound are often complicated. Sea-land breeze effects, mountain-valley flows, and the complex terrain all play an important role in the frequent changes of wind flow and boundary-layer structure.

This is particularly evident in the results for the summer simulations, where the airmass over the GVRD/FVRD, Vancouver Island, Strait of Georgia, and Puget Sound, oscillates back and forth across the Canada/U.S. border. The NOUS and NOCAN simulations indicate that, for these specific meteorological and synoptic patterns, local/urban-scale air quality impacts from transboundary transport occur along the border (within ±50 km) with some frequency. However, the incidence of long-range/regional transport (over 100 km) was low. The long-range transport results may be different for other study periods with different meteorology.

The winter simulations are indicative of a bigger long-range transport issue. For example, during December 06-10, with a southeast wind pattern, plumes travel from the Seattle area to Vancouver Island. Due to the combination of geography, nature of emissions, and regional wind flow patterns, there is little longer range transboundary transport evident elsewhere in the model domain.

In summary, based on these model results, there appear to be different regimes of transboundary pollutant transport that depend on the specific meteorological conditions and geography of the region. Long-range transport does occur, but less often than the more local-scale transboundary transport. Local transboundary transport occurs all along the B.C./Washington border, particularly in the vicinity of the GVRD and southern Vancouver Island.

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