Air Quality and Acid Deposition Forecast of South Athabasca Oil Sands Development Applying CMAQ Model

Wen Xu*
Alberta Environment and Parks, Edmonton, Alberta, Canada
Xin Qiu
Novus Environmental Inc., Guelph, Ontario, Canada

1. INTRODUCTION

In situ oil sands development is expected to dominate bitumen production in the coming decades and much of it will be located in the south Athabasca oil sands area (SAOS). In order to assess impact of environmental footprints of oil sands production in the future as the air portion of SAOS regional strategic assessment, air quality in SAOS for baseline case in year 2010 was simulated and the modeling results were evaluated with monitoring data as a foundation of this assessment (presented in CMAS 2014 annual conference; Xu, et al. 2014). Based on developed emission inventories and modelling inputs for forecasted future development scenarios, this study (Part 2) applies CMAQ model to simulate the ground level concentrations of ozone, $PM_{2.5}$, PM_{10}, NO_2, SO_2, CO, and acid deposition in SAOS for future development scenarios of high and low production levels in year 2020, and high production level in year 2050.

The CMAQ predictions for 2020 low production, 2020 high production and 2050 high production scenarios demonstrate the estimated impacts of future development scenarios on ambient air quality in the SAOS. By comparing air quality forecasts of the future scenarios with baseline year 2010, CMAQ model predicts almost no change of ground level SO_2 concentrations, slight increases of ground level NO_2 and CO concentrations, slight decrease of O_3, smaller increase of $PM_{2.5}$ and PM_{10} concentrations in the major part of SAOS area and larger increase of $PM_{2.5}$ and PM_{10} concentrations in the southern portion of SAOS area. In addition, areas in SAOS exceeding provincial standard of annual total deposition for all the future year scenarios shrink but annual total deposition increases locally nearby sites of newly commissioned central processing plants in the future scenarios.

With the comparisons amongst future scenarios including 2020 low production, 2020 high production and 2050 high production, the model predicts no significant difference between future scenarios of 2020 low production and 2020 high production for O_3, $PM_{2.5}$, PM_{10}, SO_2, NO_2, CO, annual nitrogen deposition, annual sulphur deposition and annual total deposition. The model also predicts insignificant difference between 2020 scenarios and 2050 high production for O_3, SO_2, NO_2, CO, but increase particularly in the southern part of SAOS for $PM_{2.5}$ and PM_{10}, and locally significant increase of annual total deposition near newly commissioned central processing plants in the 2050 high production scenario.

2. SUMMARY of FUTURE YEAR SCENARIOS for SAOS DEVELOPMENT in 2020 and 2050

2.1 SAOS RSA Forecasted Bitumen Production Scenarios

Three future bitumen production scenarios respectively at high, medium and low production levels were forecasted dynamically over more than 50 years (Environ and Novus, 2014). These three bitumen production scenarios for the SAOS area were developed to reflect potential impacts of future development on environment, based on economy and society development forecast, particularly oil sands production increase in the future. Due to computational time limitation, snapshots are applied for year 2020 and 2050. Besides 2010 baseline year was simulated for model evaluation in the first part of this research (Xu, et al. 2014); Year 2020 is simulated for 3 production scales: high, medium and low; Year 2050 for high production is simulated to explore possible local effects of source location variation and impacts of further production increase.

**Corresponding author:* Wen Xu, Alberta Environment and Parks, 10025 - 106 Street , Edmonton, Alberta, T5J 1G4; e-mail: wen.xu@gov.ab.ca

In this study, simulation for medium production was performed but the results show that there is not much difference between the impacts of air pollutions on air quality at the high and low production level, let alone medium production. Therefore, model simulation results for 3 future development scenarios are presented in this study, including 2020 low and high production, and 2050 high production scenarios.

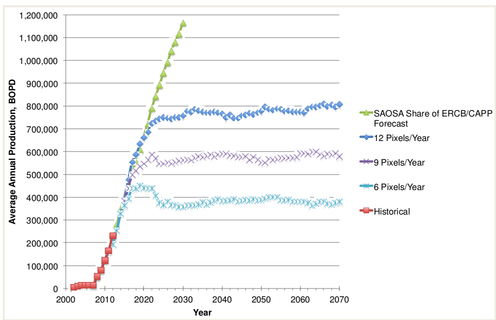

Figure 2-1 SAOS RSA forecasted production scenarios based on number of SAGD pad-pairs added annually (Environ and Novus, 2014).

2.2 Forecast of Central Processing Plants and Well Pad-pairs under Low, Medium and High Energy Development Scenarios

Based on the assumption in the future development scenarios that each township under in-situ development has a central processing plant at its township center, these pictures in Figure 2-2 show us spatial distribution of the central processing plants to be in operation and facilities to be decommissioned in future production expansion (Environ and Novus, 2014).

3. SOURCE EMISSIONS FORECAST and CMAQ MODELING METHODOLOGY

Pollutant emission rates of the existing in-situ facilities in operation at various production scales were established. Nonlinear relationships (Figure 3-1) of emission rates versus production levels were regressed and applied to estimating emission rates of air pollutants from the to-be-built central processing plants in the future scenarios.

There are 3 tiers of modelling domain in this study: 36 km resolution domain – western US and Canada, 12 km resolution domain – provincial scale and 4 km resolution modelling domain – SAOS area, i.e., the research area (Figure 3-1). Simulation for each coarser domain generates boundary condition and initial condition for the finer domain.

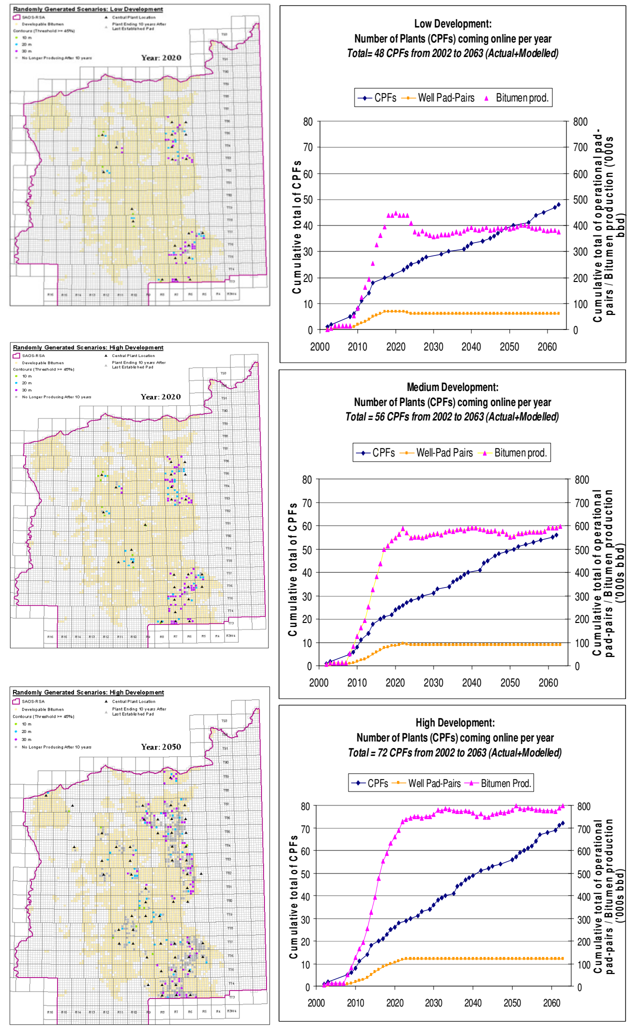

Figure 2-2 50-year forecasts and spatial distribution snapshot of bitumen production, central processing plants and well pad-pairs for low and high energy development scenarios in 2020 and high energy development scenario in 2050, sequentially (Environ and Novus, 2014).

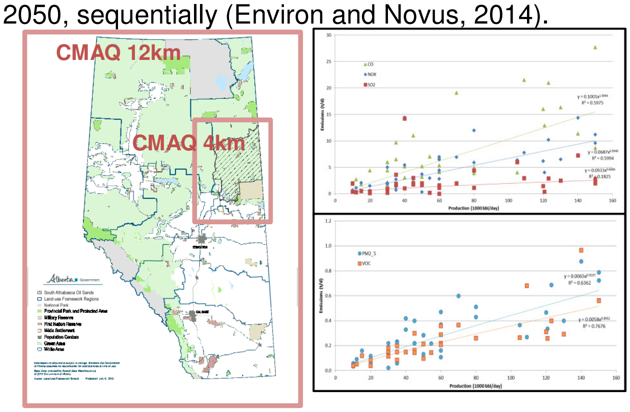

Figure 3-1 Provincial and Research Modelling Domain and Nonlinear relationships regression of emission rates versus production levels

4. CMAQ MODELING RESULTS of OZONE and $PM_{2.5}$ for YEAR 2020 and 2050 FUTURE SCENARIOS

4.1 1-hour/8-Hour Average Ozone Modelling Results

The three figures in the left column in Figure 4-1 compare differences of maximum 1-hour average ozone concentrations between baseline year and future scenarios. All the comparisons depict to us that within SAOS area, there is insignificant change of ozone concentrations in the projected future year scenarios, compared over the baseline.

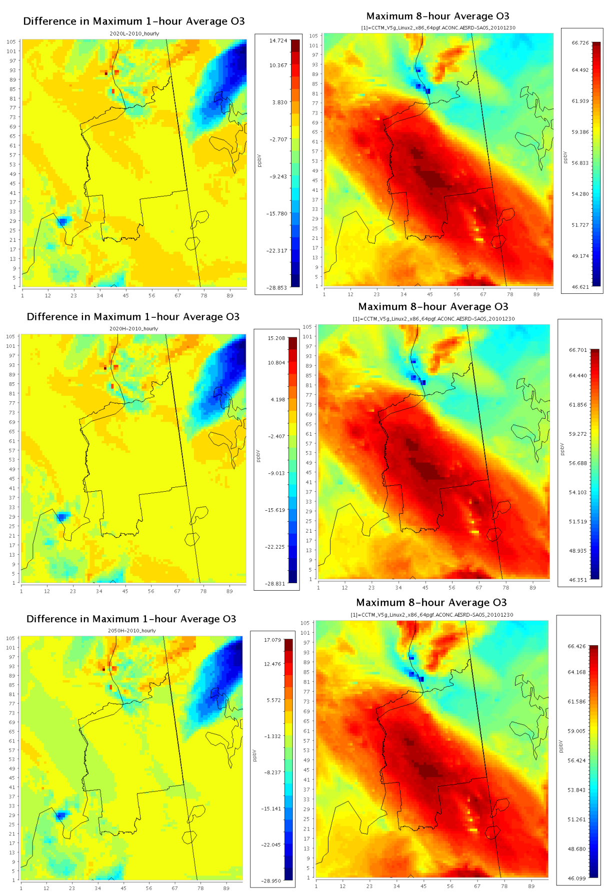

Figure 4-1 CMAQ-estimated maximum 1-hour average ozone concentration difference from baseline year (left) and maximum 8-hour ozone concentrations (right) for the 2020 low and high and 2050 high production scenarios, sequentially and respectively.

The three figures in the right column in Figure 4-1 compare maximum 8-hour average ozone concentrations among the three future scenarios. All the comparisons depict to us that within SAOS area, there is insignificant difference of ozone concentrations in the projected future year scenarios. This comparison also shows insignificant difference amongst the 3 future scenarios.

4.2 24-Hour Average $PM_{2.5}$ Modelling Results

Figure 4-2 compares the highest 24-hour average $PM_{2.5}$ concentrations between future scenarios and the baseline. For the two 2020 scenarios, the concentrations increase in SAOS area and significantly increase in southern portion of SAOS;

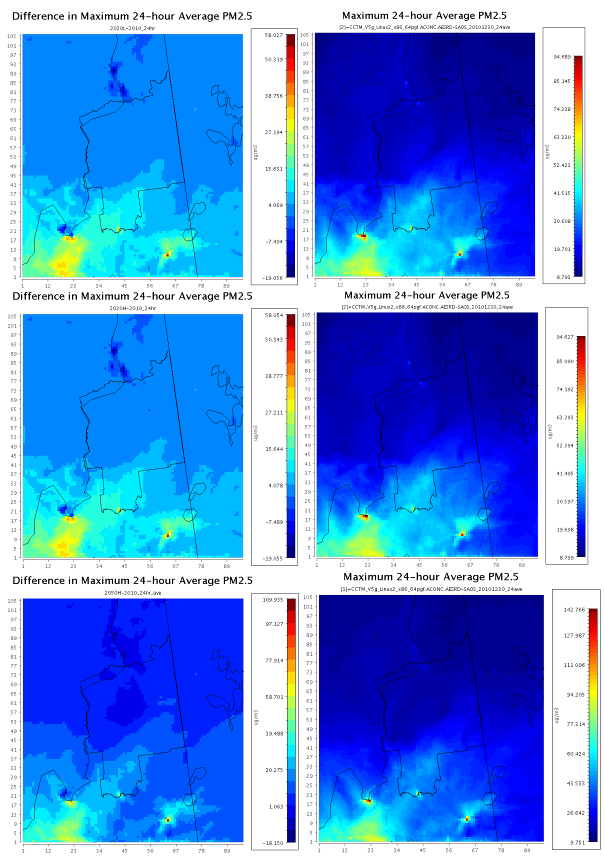

Figure 4-2 CMAQ-estimated maximum 24-hour average $PM_{2.5}$ concentration difference from baseline year (left) and maximum 24-hour $PM_{2.5}$ concentrations (right) for the 2020 low and high and 2050 high production scenarios, sequentially and respectively.

and for the 2050 high production scenario, the concentrations significantly increase in SAOS with larger increase in southern portion of SAOS. Moreover, the figures also indicate insignificant difference between 2020 low and high production scenarios, but significant increase in 2050 scenario in comparison to 2020 scenarios.

4.3 Annual Average Ozone and PM2.5 Modelling Results

Figures in left column of Figure 4-3 compare differences of future scenarios' annual average ozone concentrations from baseline case. There is insignificant difference between 2020 low and high production scenarios, but slight decrease of annual average ozone for 2050 high production scenario, compared to the two 2020 scenarios.

Consistently, the comparison of annual average $PM_{2.5}$ concentrations among the 2020 and 2050 future scenarios in right column of Figure 4-3 shows insignificant difference between 2020 low and high production scenarios, but significant increase in 2050 high production scenario compared to 2020 scenarios.

Also consistently with baseline, within SAOS boundary, the predicted annual $PM_{2.5}$ concentrations are very low and the relatively higher concentrations nearby sources can be more attributable to direct emissions of PM_{10} and primary $PM_{2.5}$ from the larger local emission sources, the contributive sources outside SAOS boundary locating at Fort McKay to Fort McMurray corridor in the north, and the primary and precursors emissions from industries, transportation and communities in the south of SAOS area.

5. CMAQ MODELING RESULTS of OZONE and $PM_{2.5}$ PRECURSORS for YEAR 2020 and 2050 FUTURE SCENARIOS

5.1 1-hour/8-Hour Average Modelling Results

The figures in Figure 5-1 show CMAQ-estimated maximum 1-hour average SO_2 and NO_2 concentrations for the future-year scenarios and their differences from the baseline. The comparison demonstrates in all the future scenarios the SO_2 concentrations significantly decrease in SAOS area, except some local increase nearby the emission sites of new central processing plants to be built in the development scenarios.

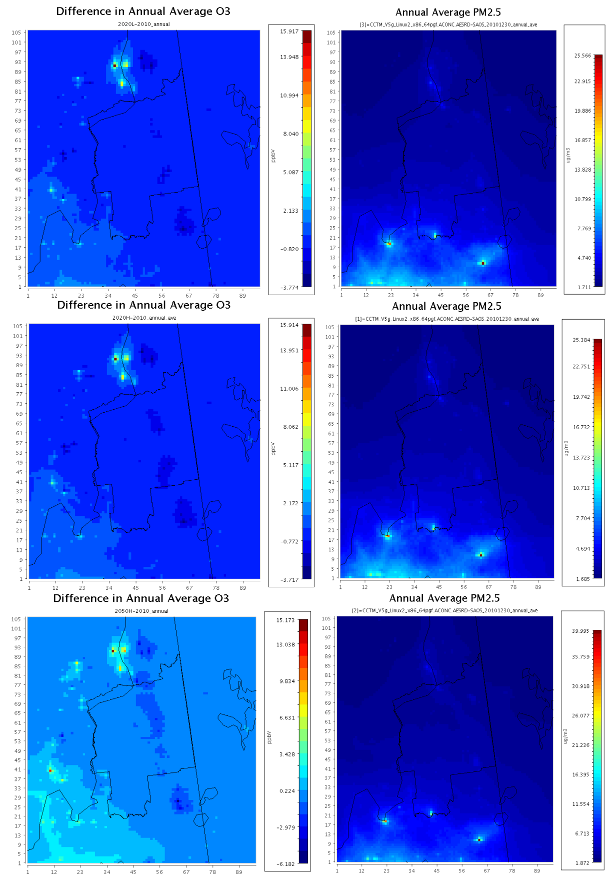

Figure 4-3 CMAQ-estimated differences of annual average ozone concentrations from baseline year (left) and annual average $PM_{2.5}$ concentrations (right) for the 2020 low and high and 2050 high production scenarios, sequentially and respectively.

The figures of CMAQ-estimated maximum 1-hour NO_2 concentrations for the future-year scenarios illustrate insignificant change or some decrease of 1-hour NO_2 concentration in most portions of SAOS area, except some locally confined increase of 1-hour NO_2 concentrations nearby the new sources (i.e., the to-be-built central processing plants), due to source location variation in these future development scenarios. The spotted effect in the figures of maximum 1-hour average NO_2 is caused by the 4 km modelling resolution, which is coarse in the condition of intensive and discrete central processing plants, and their relatively more significant NO_2 emissions in the future development scenarios.

Figure 5-2 shows maximum 8-hour average CO concentrations and differences of maximum 1-hour average CO concentrations from baseline for the future scenarios. The comparison shows insignificant change for all these scenarios.

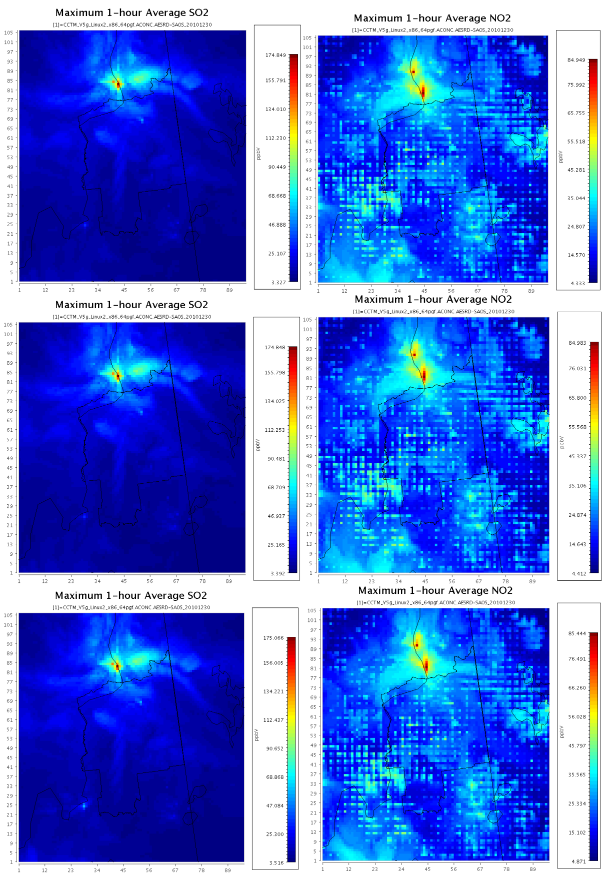

Figure 5-1 CMAQ-estimated maximum 1-hour average SO_2 (left) and NO_2 (right) concentrations for the 2020 low and high and 2050 high production scenarios, sequentially and respectively.

5.2 24-Hour Average Modelling Results

Figure 5-3 demonstrates similar results of maximum 24-hour average SO_2, NO_2 and PM_{10} concentrations for the future-year scenarios and maximum 24-hour average PM_{10} concentrations changes from the baseline.

The figures illustrate similar effect of source location variation in these future development scenarios, on maximum 24-hour NO_2 concentrations in the 4 km resolution modelling domain.

With similarity to $PM_{2.5}$ simulation, there are PM_{10} concentration increases in SAOS area in all the future scenarios, particularly more significant increase in the southern SAOS and for the 2050 scenario.

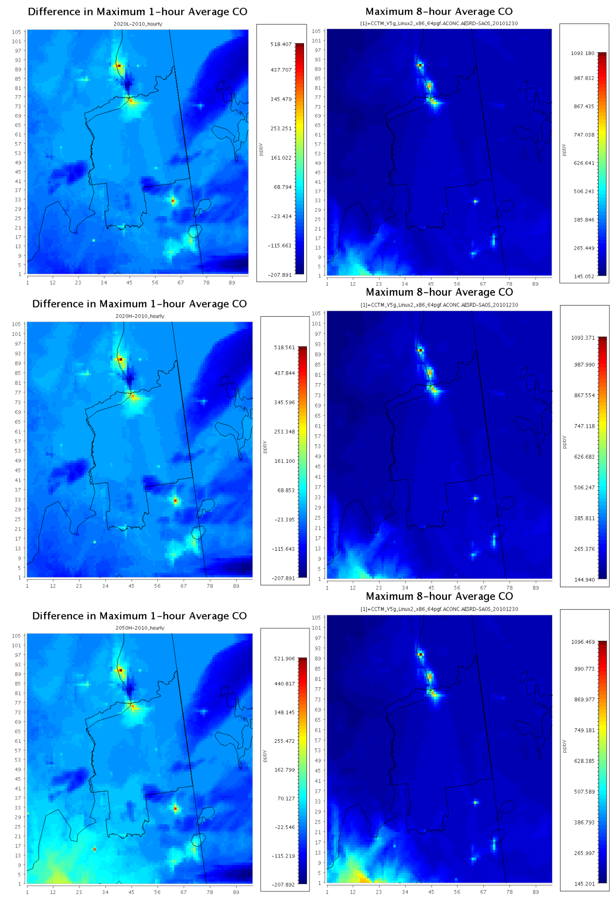

Figure 5-2 CMAQ-estimated maximum 1-hour (left) and maximum 8-hour (right) average carbon monoxide concentrations for the 2020 low and high and 2050 high production scenarios, sequentially and respectively.

Simulations and especially the dynamic vector flow simulation which cannot be presented here, also imply the increases and significant impact are mainly attributable to the sources outside SAOS area, including industrial sources and non-industrial sources such as transportation, commercial and residential heating and construction.

5.3 Annual Average Modelling Results

Figure 5-4 demonstrates SO_2 and NO_2 annual average concentrations and their differences from the baseline for the development scenarios. The comparison among them shows insignificant difference between 2020 low and high productions, except some locally confined increase nearby the new sources; but significant increase in 2050 high production scenario.

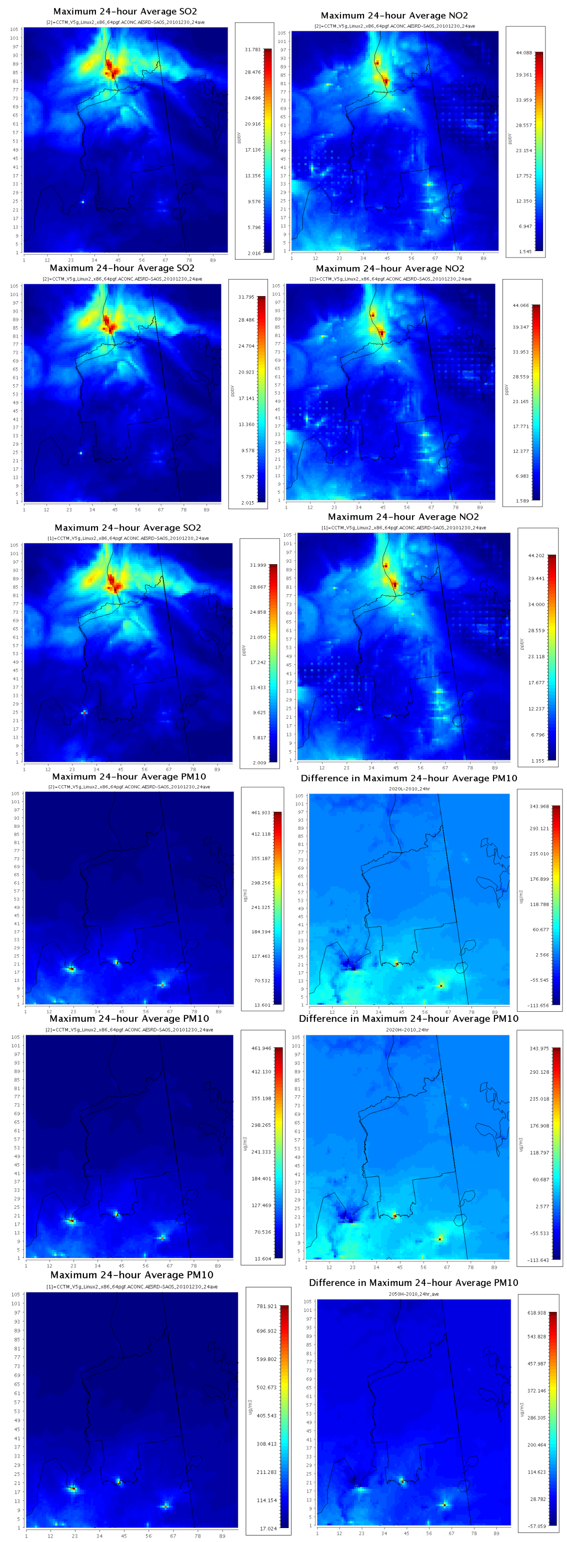

Figure 5-3 CMAQ-estimated maximum 24-hour average SO_2 (3 figures at upper left), NO_2 (3 figures at upper right) and PM_{10} (3 figures at lower left) concentrations and differences of maximum 24-hour average PM_{10} concentrations from baseline year (3 figures at lower right) for the 2020 low and high and 2050 high production scenarios, sequentially and respectively.

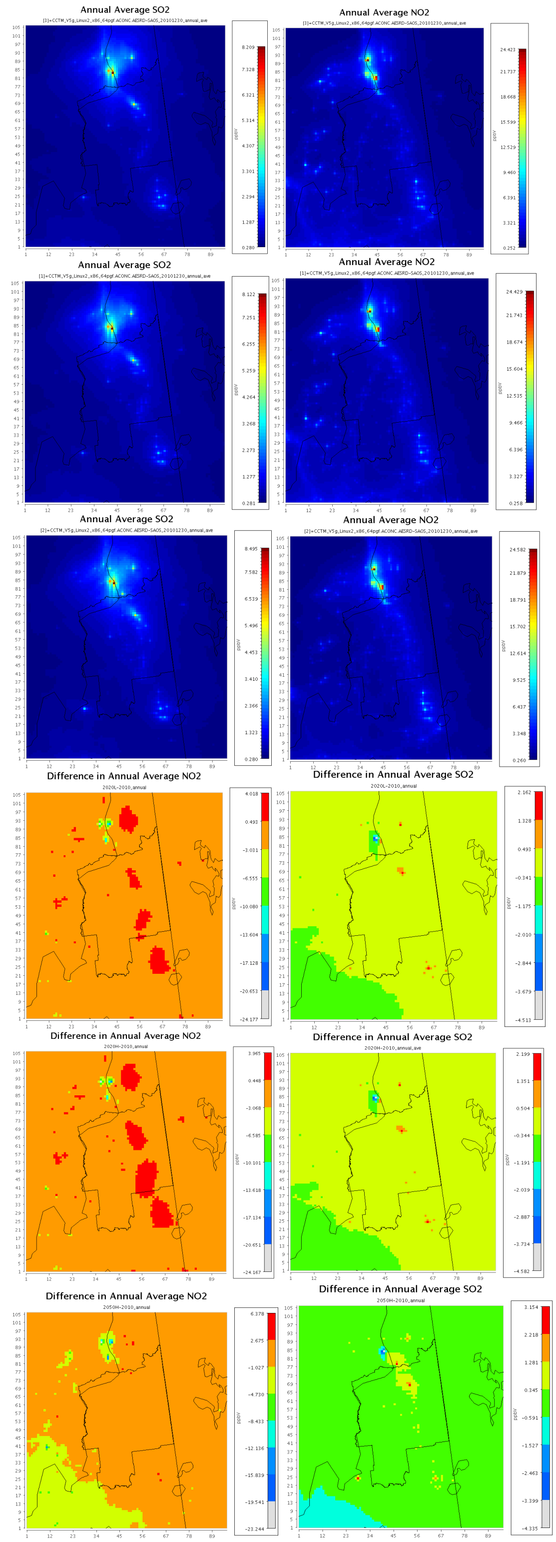

Figure 5-4 CMAQ-estimated annual average SO_2 (3 figures at upper left), NO_2 (3 figures at upper right) concentrations and their differences from baseline year (3 figures at lower right, 3 figures at lower left) for the 2020 low and high and 2050 high production scenarios, sequentially and respectively.

Figure 5-5 presents PM_{10} and $PM_{2.5}$ annual average concentrations differences from the baseline for the development scenarios. Similar to 1-hour and 24-hour average $PM_{2.5}$ and PM_{10} concentrations, there are $PM_{2.5}$ increases in SAOS area for all the future scenarios. However, the increase is insignificant between 2020 low and high production scenarios, but there is significant increase for 2050 high production scenarios, particularly in the southern SAOS.

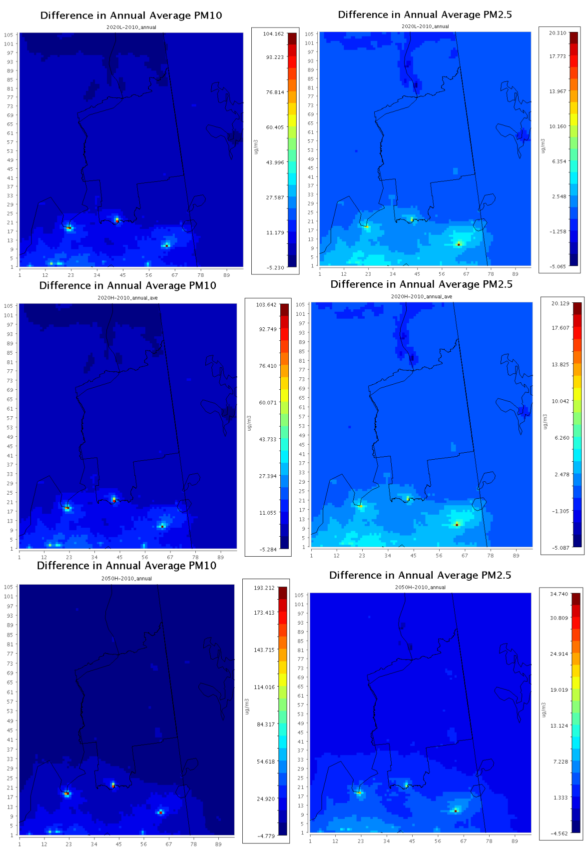

Figure 5-5 CMAQ-estimated differences of annual average PM_{10} (left) and $PM_{2.5}$ (right) concentrations from baseline year for the 2020 low and high and 2050 high production scenarios, sequentially and respectively.

6. CMAQ MODELLING RESULTS of NITROGEN and SULPHUR TOTAL DEPOSITION for YEAR 2020 and 2050 FUTURE SCENARIOS

As mentioned in the first part of research (Xu, et al. 2014), the majority of SAOS area is classified as highly sensitive to acid deposition (AENV, 2008). The calculations of CMAQ-estimated sulphur and nitrogen deposition in the 4 km resolution modelling domain were also performed for the future scenarios.

The figures in Figure 6 compare CMAQ-estimated annual total acid deposition (nitrogen and sulphur) across the 4 km resolution domain for future scenarios. The comparison shows insignificant difference between 2020 low and high production scenarios; but in 2050 high production scenario, compared to the 2020 scenarios, in the northern SAOS, there is slightly spatial expansion of areas with acidic deposition exceeding 250 H^+ eq/ha/yr management trigger level of critical load for high sensitivity area.

In addition, comparing the 3 future development scenarios to the baseline year, there is insignificant change of annual acidic nitrogen and sulfur deposition for most areas in SAOS, except some locally decrease and increase due to source location variation, particularly in 2050 high production scenario.

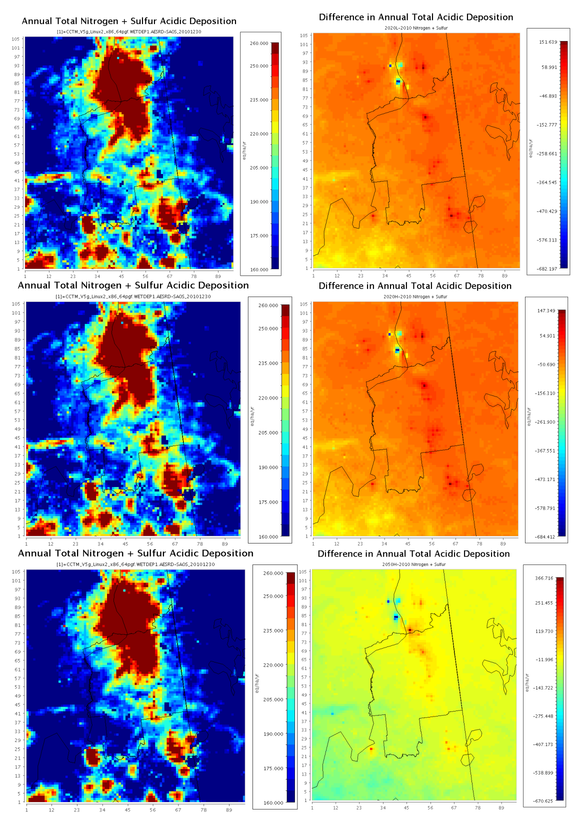

Figure 6-1 CMAQ-estimated annual total nitrogen and sulphur deposition (left) and acidic deposition differences from baseline year (right) for the 2020 low and high and 2050 high production scenarios, sequentially and respectively (unit in H^+ eq/ha/year).

It is also noticeable that in general, apparently the areas exceeding the management trigger level shrink for the future year scenarios in comparison to the 2010 baseline. The larger area shrink indicated in the north is mainly attributable to a desulphurization facility going into operation in 2013. Other contractions of above-trigger-level areas such as in SAOS and the south of the 4km modelling domain are also caused by more scattered NO_x and SO_2 emissions in future SAOS development scenarios, and more importantly by much larger reduction of SO_2 emissions than the net increase of nitrogen oxides (NO_x) emissions in future development scenarios in the 4km modelling domain. SO_2 emission decrease is attributed to the emission reduction in industries and transportation due to more stringent regulation in SO_2 emission. It's justified to see the consistency between the results and SO_2 and NO_2 annual average concentrations.

7. SUMMARY of CMAQ MODELLING RESULTS for FUTURE SCENARIOS and COMPARISON with BASELINE

Table 7-1 summarizes the comparison between simulated maximum ambient concentrations of particulate matter (PM), ozone and their precursors in the 4 km resolution modelling domain for baseline and future development scenarios. The comparison of the 3 future scenarios and the baseline case indicates that, except slight decrease of ozone and increase of PM including $PM_{2.5}$ and PM_{10}, there is no significant change for the other pollutants in the baseline and future development scenarios.

8. CONCLUSIONS

In conclusion, the impacts of future oil sands development were estimated with CMAQ, with comparing baseline year 2010, future scenarios 2020 low production, 2020 high production and 2050 high production.

By the comparison of future scenarios with the baseline modelling, CMAQ model predicts the future development scenarios with:

-- Almost no change of ground level SO_2 concentration;

-- Slight increase of ground level NO_2 and CO concentration;

-- Slight decrease of ground level O_3;

-- Smaller increase of $PM_{2.5}$ and PM_{10} concentrations in the major part of SAOS area,

Table 7-1 Summary comparison of CMAQ-estimated maximum ambient concentrations of particulate matter (PM), ozone and their precursors in the 4 km resolution modelling domain (Units are expressed in ppb for gas and μg/m^3 for PM).

Pollutant	Avg. Time	CMAQ estimated concentration*				
		Min/ Max	Base Case	2020 L	2020 H	2050 H
O_3	annual	Min	10	13	13	13
		Max	35	35	35	35
O_3	24-hour	Min	36	38	38	37
		Max	62	62	62	62
O_3	1-hour	Min	48	51	51	50
		Max	87	80	80	80
O_3	8-hour	Min	44	47	46	46
		Max	74	67	67	66
$PM_{2.5}$	annual	Min	1.7	1.7	1.7	1.9
		Max	9.2	25.6	25.4	40
$PM_{2.5}$	24-Hour	Min	8	9	8	10
		Max	89	95	95	143
$PM_{2.5}$	1-Hour	Min	10	13	13	16
		Max	613	204	204	353
SO_2	annual	Min	0.4	0.28	0.28	0.28
		Max	11	8	8	8
SO_2	24-hour	Min	2	2	2	2
		Max	86	32	32	32
SO_2	1-hour	Min	5	3	3	4
		Max	509	175	175	175
PM_{10}	annual	Min	2	2	2	2
		Max	25	129	129	218
PM_{10}	24-hour	Min	9	14	14	17
		Max	576	462	462	782
CO	8-hour	Min	147	145	145	145
		Max	1008	1093	1093	1096
CO	1-hour	Min	158	148	148	148
		Max	1320	1632	1632	1635
NO_2	annual	Min	0. 3	0. 25	0. 26	0. 26
		Max	31	24	24	25
NO_2	24-hour	Min	2	2	2	1.4
		Max	65	44	44	44
NO_2	1-hour	Min	5	4	4	5
		Max	140	85	85	85

*The CMAQ estimations are provided on a 4km modelling domain-wide basis which covers the entire SAOS. Maximum values represent CMAQ-estimated maximum concentrations of a chosen metric. Units are in ppb except μg/m^3 for $PM_{2.5}$ and PM_{10}.

and larger increase of $PM_{2.5}$ and PM_{10} concentrations in the southern portion of SAOS area; and

-- Areas in SAOS exceeding management trigger level of annual acid deposition shrink, but locally confined annual nitrogen and sulphur acidic deposition increases nearby sites of central processing plants, which will be put into production in future scenarios.

With respects to the comparisons amongst future scenarios, the model predicts:

-- No significant difference between future scenarios of 2020 low and high production for O_3, $PM_{2.5}$, PM_{10}, SO_2, NO_2 and CO ground level concentrations, annual nitrogen deposition, annual sulphur deposition and annual total acid deposition (total nitrogen and sulphur); and

-- No significant difference of 2050 high production from 2020 scenarios for O_3, SO_2, NO_2, CO concentrations, except increase particularly in the southern part of SAOS for $PM_{2.5}$ and PM_{10} concentrations, and locally significant increase of annual acid deposition (total nitrogen and sulphur) near central processing plants to be commissioned in the 2050 scenario.

In summary, the model predicts the potential issue caused by future development may be $PM_{2.5}$ and PM_{10} in the 2050 high production scenario. Nonetheless, the issue may mainly exist in the southern part of SAOS area and can be mainly attributable to emissions from the sources outside of the SAOS boundary, including sources in the south of SAOS, such as community, industry and traffic sources in Northern Saskatchewan region, particularly in the Edmonton capital region, and other regional background contributors.

Besides inherent limitation and uncertainty of the model, the modelling results strongly rely on the accuracy of modelling inputs, especially meteorological data and emissions inventories. While emissions inventories for baseline and future year scenarios were investigated to the best knowledge as possible (based on the best available data), the results are also based on forecasted anthropogenic emissions which were not intended to be the definitive representations of emissions in the forecast periods. In addition, the 2010 meteorology was hypothetically applied to future year scenarios. Therefore, this model forecast should be considered as a useful "range-finding" tool in comparing the future-year scenarios with the baseline case. In this study, the modelling results for the 2010 baseline year were used as a benchmark in comparison to future development scenarios. The relative comparison amongst future scenarios and the baseline should be more meaningful.

9. REFERENCES

1. AENV. 2008. Dry Deposition Monitoring Methods in Alberta. Alberta Environment, Edmonton, AB. February.

2. Environ and Novus, 2014. Development of Air Emissions Inventories and Inputs to Support Air Quality Modelling of Selected Pollutants using Community Multiscale Air Quality (CMAQ) and Long Range Dispersion CALPUFF Model for the South Athabasca Oil Sands Area (SAOS). Novato, CA; Guelph, Ontario. July.

3. Xu, W., F. Yang, N. Walters, and X. Qiu, 2014, Air Quality and Acid Deposition Simulation of South Athabasca Oil Sands Area Applying WRF, CMAQ and CALPUFF Models, and Model Performance Evaluations of WRF and CMAQ Models. Presented at the 2014 Annual CMAS Conference, Chapel Hill, NC. October.