Atmospheric Environment 141 (2016) 209–218

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

Photochemical model evaluation of the ground-level ozone impacts on ambient air quality and vegetation health in the Alberta oil sands region: Using present and future emission scenarios

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HIGHLIGHTS

- CMAQ model was applied to assess ozone formation and impacts on air and vegetation.
- The potential impacts of current and possible future emission scenarios were assessed.
- Ozone in current and future year emission scenarios did not exceed relevant standards.
- The chronic 3-months SUM60 exposure metric is within the criteria baseline range.

ARTICLE INFO

Article history:
Received 12 March 2016
Received in revised form
4 June 2016
Accepted 20 June 2016
Available online 21 June 2016

Keywords:
Ground-level ozone
Community Multi-scale Air Quality model
Athabasca oil sands region
Air quality
Ozone impact on vegetation
Emission scenarios

ABSTRACT

One of the potential environmental issues associated with oil sands development is increased ozone formation resulting from NO_X and volatile organic compound emissions from bitumen extraction, processing and upgrading. To manage this issue in the Athabasca Oil Sands Region (AOSR) in northeast Alberta, a regional multi-stakeholder group, the Cumulative Environmental Management Association (CEMA), developed an Ozone Management Framework that includes a modelling based assessment component. In this paper, we describe how the Community Multi-scale Air Quality (CMAQ) model was applied to assess potential ground-level ozone formation and impacts on ambient air quality and vegetation health for three different ozone precursor cases in the AOSR. Statistical analysis methods were applied, and the CMAQ performance results met the U.S. EPA model performance goal at all sites. The modelled 4th highest daily maximum 8-h average ozone concentrations in the base and two future year scenarios did not exceed the Canada-wide standard of 65 ppb or the newer Canadian Ambient Air Quality Standards of 63 ppb in 2015 and 62 ppb in 2020. Modelled maximum 1-h ozone concentrations in the study were well below the Alberta Ambient Air Quality Objective of 82 ppb in all three cases. Several ozone vegetation exposure metrics were also evaluated to investigate the potential impact of ground-level ozone on vegetation. The chronic 3-months SUM60 exposure metric is within the CEMA baseline range (0–2000 ppb-hr) everywhere in the AOSR. The AOT40 ozone exposure metric predicted by CMAQ did not exceed the United Nations Economic Commission for Europe (UN/ECE) threshold of concern of 3000 ppb-hr in any of the cases but is just below the threshold in high-end future emissions scenario. In all three emission scenarios, the CMAQ predicted W126 ozone exposure metric is within the CEMA baseline threshold of 4000 ppb-hr. This study outlines the use of photochemical modelling of the impact of an industry (oil sands) on ground-level ozone levels as an air quality management tool in the AOSR. It allows an evaluation of the relationships between the pollutants emitted to the atmosphere and potential ground level ozone concentrations throughout the AOSR thereby extending the spatial coverage of the results beyond the monitoring network and also allowing an assessment of the potential impacts of possible future emission cases.

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http://dx.doi.org/10.1016/j.atmosenv.2016.06.053
1352-2310/

1. Introduction

Alberta's oil sands represent the world's third largest proven reserve of crude oil and consist of three deposits; the Athabasca oil sands region (AOSR) which is the largest and the Peace River and Cold Lake oil sands regions all located in the North-eastern Alberta, Canada (GoA, 2014). The AOSR is heavily developed: as of September 2015, there were 46 operating oil sands extraction projects including 4 with upgraders as well as 59 additional projects that are approved or planned (Alberta oil sands industry quarterly update, Fall, 2015; Court, 2010; Alberta Energy, 2016). The AOSR was the focus of this study. Oil sands developments are major emission sources of ozone precursors, oxides of nitrogen (NO_X) and volatile organic compounds (VOCs) (Davies et al., 2012) and ozone impacts have been identified as a potential health and environmental impact associated with oil sands development (Alberta Environment, 1999; Percy et al., 2012). In 2006, a regional ozone management framework (hereafter "the Framework") was developed by the Cumulative Environmental Management Association (CEMA), which is a multi-stakeholder society in Northeast Alberta (CEMA, 2006). Initially the Framework focused on health effects but it was subsequently expanded to include vegetation effects based on a study CEMA had conducted on ozone vegetation metrics (AMEC Earth and Environmental, 2006). A further review of ozone vegetation metrics was undertaken by CEMA in 2011 (A.S.L. and Associates, 2011). A key element of the Framework is modelling to determine the status of the study area, in current and future timeframes with respect to the established health-related and vegetation damage ozone criteria.

Ozone has a high oxidant capacity that can cause adverse effects on human health (i.e., respiratory irritations and illnesses, especially children and the elderly and people already suffering from some respiratory system deficiency) (WHO, 2006; Rojas, 2014). Elevated ozone concentrations can also cause damage to vegetation (affecting growth and physiology, foliar damage and reducing crop yields and seed production) as well as adversely affecting materials (promoting corrosion and aging processes) (WHO, 2006; Martuzzi et al., 2006). Ground-level ozone is the most damaging air pollutant to crops and ecosystems (http://www.sciencedirect.com/science/article/pii/S1352231011000070 Heagle, 1989). Ozone enters leaves through plant stomata during the normal gas exchange. As a strong oxidant, ozone and its secondary by-products damage vegetation by reducing photosynthesis and other important physiological functions, resulting in weaker, stunted plants, inferior crop quality, and decreased yields (http://www.sciencedirect.com/science/article/pii/S1352231011000070 Fiscus et al., 2002; http://www.sciencedirect.com/science/article/pii/S1352231011000070 Fiscus et al., 2005; http://www.sciencedirect.com/science/article/pii/S1352231011000070 Morgan et al., 2003; http://www.sciencedirect.com/science/article/pii/S1352231011000070 Booker et al., 2005; http://www.sciencedirect.com/science/article/pii/S1352231011000070 Fuhrer, 2009; Avnery et al., 2011).

Modelling is one of the three ozone management tools established by the Framework (monitoring and emissions management are the other two). Modelling is the tool used to identify the potential for ozone related health and/or vegetation impacts associated with proposed and planned developments. This type of potential future cumulative effects modelling for ozone provides information that can be used to proactively manage development and its emissions. As there can be significant financial implications associated with development restrictions and/or additional emission controls, it is important that the modelling predictions upon which such management actions are based be as reliable as is technically possible. The photo-chemical modelling outlined in this study focused on providing future predictions that could be used to guide policy development and proactive management decision. The scientific importance of this study is for forecasting ambient air quality using future estimated emissions to develop appropriate and proactive management strategy and action in the heavy industrial area. In addition, the use of numerical models for regional air quality evaluation and management allows an assessment of the relationships between the pollutants emitted to the atmosphere and the pollution measured at ground-level by the monitoring networks (Thunis et al., 2012; Sokhi et al., 2006). It also overcomes the issues of the limited spatial coverage of monitoring data and the regional representativeness of this data (Anh et al., 1998).

The objectives of this study were to: i) understand the potential for photochemical production of ozone in the AOSR due to ozone precursor NOx and VOC emission sources; ii) estimate existing and potential future regional ambient ozone concentrations under specified development and emission scenarios; iii) compare these estimates to Framework human health-related levels/criteria; and iv) estimate regional ozone exposure levels to vegetation and compare these exposure estimates to relevant criteria. Another objective of the study was to provide information that could be used to select the vegetation ozone metrics that should be used in future modelling assessments.

2. Methodology

2.1. Study area

The Community Multiscale Air Quality (CMAQ; Version 5.0.1) Chemical Transport Model (CTM) developed by the United States Environmental Protection Agency (U.S. EPA) (U.S. EPA, 1999; Byun and Schere, 2006; Foley et al., 2010) was applied in this study. The CMAQ nested modelling domain used for this study is shown in Fig. 1. The innermost domain at 4 km horizontal resolution covers the AOSR in Northeast Alberta and was similar to the domain used earlier for modelling in the AOSR (Cho et al., 2012). The 4 km domain is nested within a 12 km domain that covers the Province of Alberta that in turn is nested within a regional 36 km resolution grid. In the 4 km domain study area, air pollutants are emitted from various emission sources including boilers, heaters, stacks, cogeneration units, upgraders, bitumen separation processes, fugitive plant emissions, mine fleet, fugitive mine faces, fugitive tailings and non-industrial activities (i.e., residential and commercial heating). Other potential sources of elevated ozone concentration in the AOSR include: 1) the long-range transport of photochemically produced ozone from upwind sources (e.g., the Edmonton region), 2) the formation of ozone in the AOSR from precursor anthropogenic and biogenic sources outside the AOSR, 3) the downward mixing of ozone-rich stratospheric air by continuous stratosphere troposphere air exchange processes or by discrete stratospheric intrusions, and 4) by photochemical production due to precursor emissions from biomass burning (e.g., wildfires). The current CMAQ application considers all of these factors through model processes and global background concentrations. Fig. S1 shows a map of the Athabasca oil sands facilities within the CAMQ modelling boundaries.

2.2. Meteorological and photochemical modelling

The CMAQ CTM meteorological inputs were generated by processing output from the Weather Research and Forecast (WRF) meteorological model (NCAR, 2011; ENVIRON and Alpine Geophysics, 2012; NOAA/NCDC, 2010; Skamarock, 2004; 2006; Skamarock et al., 2005; 2008) using the Meteorological Chemistry Interface Processor (MCIP: http://www.cmascenter.org/help/model_docs/mcip/4.1/ReleaseNotes). A detailed WRF model setup