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Assessment of regional acidifying pollutants in the Athabasca oil sands area under different emission scenarios

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HIGHLIGHTS

- The CMAQ model is used to estimate acid deposition using four emission scenarios.
- Sulphur and nitrogen deposition constitute 40% and 60% of the total PAI deposition.
- Nitrogen deposition increases 12% between existing and future emission scenarios.
- Study results support management priorities and deposition impact minimization.

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ABSTRACT

Acid deposition is a potential environmental impact of oil sands development in the Athabasca Oil Sands Region (AOSR) in Northeastern Alberta. An acid deposition management framework has been established to manage this issue. This framework includes an acid deposition modelling and time-to-effect impact assessment component that was recently implemented for four acidifying emissions cases using the Community Multi-scale Air Quality (CMAQ) model. Predicted gross Potential Acid Input (PAI) deposition in the AOSR increases from the historical to existing case with further increases predicted in two future cases due to the projected increase in NOx emissions. On average the total predicted PAI deposition in the AOSR is approximately 40% sulphur deposition and 60% nitrogen deposition. Sulphur deposition decreases by 7% from the historical to existing cases due to the reductions in SO_2 emissions that have occurred in the AOSR but increases by 5% from the existing to future case 1 and by 8% from existing to future case 2 even though continued AOSR SO_2 emission decreases were modelled. This is likely the result of the deposition reduction associated with a single large reduction in SO_2 emissions from one facility's main stack being offset elsewhere in the AOSR by deposition increases due to small increases in SO_2 emissions from several in situ sources with shorter stacks. Average nitrogen deposition over the AOSR increases by 10% from the historical to existing case and then further increases by 10.6% from the existing case to future case 1 and by 12.3% from the existing case to future case 2. The increasing relevance of NOx emissions over SO_2 emissions in the AOSR suggests that a robust treatment of nitrogen chemistry such as in CMAQ is required for conducting deposition assessments in the region. The modelling results provide information that can be used to inform oil sands emission management priorities in the context of acid deposition and nitrogen eutrophication impact minimization.

1. Introduction

Canada has the third-largest reserves of recoverable oil in the world, after Saudi Arabia and Venezuela. Of the current estimated 173 billion barrels of recoverable oil in Canada, 170 billion barrels (97%) are located in Alberta, and about 168 billion barrels (97%) are

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associated with oil sands (bitumen) deposits (Stringham, 2012). There are three major bitumen deposits in Alberta. The largest is the Athabasca deposit, which is located in the Regional Municipality of Wood Buffalo (RMWB) in northeast Alberta that is called the Athabasca Oil Sands Region (AOSR; Alberta oil sands industry quarterly update, 2015). Total annual operating and capital expenditures associated with oil sands development have been estimated to average approximately $55 billion Canadian dollars annually for the period 2013 to 2038 and beyond (Canadian Energy Research Institute, 2014) making the oil sands an important natural resource providing significant economic benefits to Canada and Alberta. Since commercial bitumen production began in 1967, production has steadily increased and is projected to grow substantially in the future (NEB, 2016). Air emissions associated with oil sands development are large (Royal Society of Canada, 2010); as of July 2014 there were 132 oil sands projects operating in Alberta and 36% and 14.6% of total provincial emissions of SO_2 and NOx, respectively, are emitted in the AOSR. In addition, the AOSR has large areas overlain with mineral soils that have some of the lowest weathering rates in Canada (Whitfield et al., 2010). This makes portions of the AOSR particularly vulnerable to the adverse environment effects of acid deposition and a wide range of acidification monitoring programs and research activities have been established which focus on this potential issue (Percy et al., 2012; Fenn and Ross, 2010; Bytnerowicz et al., 2010; Abboud et al., 2012). These acid deposition related activities have recently been enhanced under the joint federal-provincial oil sands monitoring program (Canada-Alberta Oil Sands Environmental Monitoring Information Portal, 2014).

Emissions of SO_2 contribute to sulphur deposition through dry gaseous deposition processes and through oxidation in the atmosphere resulting in sulphuric acid (H_2SO_4) and subsequent aerosol formation (e.g., ammonium sulphate) followed by dry or wet deposition (Fowler, 2002; Jacob, 1999). Emissions of NOx are subject to a number of possible atmospheric transformations (Crutzen, 1979) that influence the form and rate of nitrogen deposition (Fowler, 2002; Munger et al., 1998). In natural environments acidification associated with acid deposition is a relatively slow process and the consequent ecological response occurs even more slowly (Gorham, 1998; Singh and Agrawal, 2008).

The Cumulative Environmental Management Association (CEMA) is a multi-stakeholder group that was formed to address a number of environmental issues in the AOSR including acid deposition (http://cemaonline.ca). In 2004, a comprehensive Acid Deposition Management Framework (ADMF) was developed by CEMA which involved a three-stage implementation process (CEMA, 2004). The ADMF includes measurable management objectives for soil (i.e., base saturation and base cation: aluminium ratio) and for aquatic systems (i.e., acid neutralizing capacity) based on both monitoring and on “time to effect” soil and aquatic modeling outputs. The ADMF is structured based on early indications of chemical change in soil and lakes and allowing only a certain level of change rather than on ecological change criteria or critical loads and as such is intended to be a proactive approach to acid deposition management. To our knowledge this approach to acid deposition modeling and management in an oil extraction impacted area is unique.

The Community Multi-scale Air Quality (CMAQ) model was used to estimate atmospheric nitrogen and sulphur deposition. Deposition predictions from this modelling were used as inputs into the Model for Acidification of Groundwater in Catchments (MAGIC) which had been parameterized for the AOSR (Cosby et al., 1985; 2001; Sullivan et al., 2007; Whitfield et al., 2009, 2010a; 2010b). To support the acid deposition modelling in the current work, a comprehensive emissions inventory for industrial and non-industrial sources for four temporal cases was developed (Davies et al., 2012).

This study focuses on the methods and results from this modelling work which involved estimating the temporal and spatial trends of annual dry, wet and total deposition of acidifying compounds using four different emission scenarios, and a comparison of model results against available monitoring data in the AOSR. The factors leading to increased acid deposition and the relationship between atmospheric concentrations and various emission cases were analyzed and used to provide guidance on possible priorities for oil sands emissions management for addressing acid deposition in the AOSR.

2. Methodology

2.1. Modeling domain and description of modeling system

The CMAQ nested modelling domain (with version 5.0.1) applied for this study is shown in Fig. 1. The innermost domain at 4 km horizontal resolution covers the AOSR in Northeastern Alberta. The 4 km domain is nested within a domain at 12 km resolution that covers the Province of Alberta that in turn is nested within a regional 36 km resolution grid covering western Canada and the northwestern U.S that provides background concentrations (boundary conditions) of pollutants transported to Alberta through regional transport. The SMOKE emissions model (version 3.0) was used to process the province-level annual anthropogenic emissions into the hourly gridded speciated emissions needed for input into CMAQ (Coats, 1996; http://cmascenter.org/smoke/). The CMAQ model configuration used in this study is shown in Table S1. Biogenic emissions based on version 2.04 of the Model of Emissions of Gases and Aerosols from Nature (MEGAN; (National Center for Atmospheric Research (NCAR), 2011; Guenther et al., 2006; Sakulyanontvittaya et al., 2008) were used in this assessment. Biomass burning emissions of NO_x, CO, VOC and PM species in the region were specified using data from the NCAR fire inventory for 2006 derived from analysis of fire locations using satellite-borne detectors (Wiedinmyer et al., 2006). SMOKE was used to merge the anthropogenic emissions with biogenic emissions to prepare CMAQ-ready emissions.

In addition, version 4.1 of the Meteorological-Chemistry Interface Program (MCIP; http://www.cmascenter.org/help/model_docs/mcip/4.1/ReleaseNotes) was used for processing the 1980 and 2010 Weather Research & Forecasting (WRF) model (version 3.4.1; National Center for Atmospheric Research, 2011) meteorological modeling outputs. The WRF model (Skamarock, 2004; 2006; Skamarock et al., 2008) was used for high resolution meteorological modelling of the Alberta region. The WRF domain consists of a system of three simultaneous 1-way nested grids (i.e., the WRF coarse grid solution affected the finer grids but the fine grid solution did not feedback to the coarser grids), with horizontal grid cells 36, 12, and 4 km in size (Fig. 1 & Fig. S1). All WRF grids are defined on a Lambert Conformal Conic (LCC) projection centered at 49°N, 121°W with true latitudes at 30°N and 60°N (Fig. S1). The WRF model uses a terrain-following hydrostatic-pressure vertical coordinate (eta) defined in Skamarock et al. (2008). The WRF domain nest, vertical layers and physics options used in this study are shown in Tables S2, S3, and S4, respectively. The Carbon Bond (CB05) photochemical mechanism (Yarwood et al., 2005) was used in this study. More detailed CMAQ and WRF models setup and configurations are described in the Supplement Information. All of the model versions used were the latest versions when the study was initiated.