Emissions Preparation for High-Resolution Air Quality Modelling over the Athabasca Oil Sands Region of Alberta, Canada

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Presentation Overview

• Joint Oil Sands Monitoring (JOSM) Plan:
  - Joint federal and Alberta governments initiative
  - One sub-project: creation of emissions files for air quality (AQ) modelling in this region

• Topics to be covered:
  - Introduction to Alberta’s oil sands and main sources of emissions
  - 2013 summer field study in this region
  - Methodology applied to emissions preparation for AQ modeling
  - One example showing AQ model forecast for flight planning during the field study
  - One example showing how aircraft measurements can help in emissions estimates
Introduction to Athabasca Oil Sands

- Oil sands (OS) are a natural mixture of sand, clay, and water, saturated with bitumen
- 71% of global OS reserves are in Alberta, Canada.
- Two primary methods of extraction:
  - open-pit surface mining
  - in-situ techniques
- Due to the nature of the extraction methodology, emissions are mostly from the surface mining area over the Athabasca Oil Sands Region (AOSR) of northeastern Alberta
- Large source of air pollutants in Alberta:
  - 2\textsuperscript{nd} largest source of SO\textsubscript{2}
  - 3\textsuperscript{rd} largest source of industrial NO\textsubscript{x} emissions
  - significant sources of industrial PM, CO and VOCs
Oil Sands Geographic Locations

The oil sands are located in three major areas in northern Alberta underlying 142,200 km².

Peace River Oil Sands

Fort McMurray

Athabasca Oil Sands

Cold Lake Oil Sands

Study Area

http://www.energy.alberta.ca/OilSands/960.asp

http://jintoilsandsmonitoring.ca/pages/map.aspx
Overview of Oil Sands Surface Mining Processes

1. **DIG**
   - Oil sand is scooped out of a giant mine and deposited onto massive, 400-ton trucks.

2. **CRUSH & MOVE**
   - Bitumen-rich sand is ground in an ore preparation plant before being sent by pipeline to the primary extraction plant.

3. **EXTRACT**
   - During the primary extraction process, the oil sand is placed in a giant tank where raw bitumen is separated from sand and water.

4. **DILUTE**
   - Bitumen is mixed with naphtha, a chemical solvent, to remove remaining minerals and water.

5. **UPGRADE**
   - To create synthetic crude oil, the bitumen is heated to 900 degrees in giant furnaces, a process that removes excess carbon. Hydrogen is added to prepare it for industrial use.

[Diagram Image](http://esplift.com/osands.jpg)
Main Sources of Emissions:
Surface Mining (fleets and mine faces)

- Mine fleets are sources of NO\textsubscript{x} and CO emissions, while mine faces are sources of VOCs emissions.

http://activerain.trulia.com/blogsview/687418/the-giants-of-mining
- In 2013, tailings ponds in the Alberta oil sands covered an area of about 77 square kilometres (30 square miles)

http://www.oilsands.alberta.ca/FactSheets/Tailings_FSht_Sep_2013_Online.pdf

Main Sources of Emissions: Tailings Ponds (VOCs)

http://earthobservatory.nasa.gov/IOTD/view.php?id=40997
Main Sources of Emissions: Upgrading Plants

- Various combustion sources and industrial processes
- Sources of $\text{SO}_2$, $\text{NO}_x$, CO, PM and VOCs

- Upgrading is to transform bitumen into synthetic crude oil
- There are 2 broad types of upgrading: primary and secondary upgrading
Monitoring a Changing Environment

- Extraction and processing of crude oil from oil sands has undergone a rapid expansion.
- Estimating environmental impacts of the emissions associated with this expansion may be accomplished using air-quality models.
- However, the models need:
  - Accurate emissions data, in order to provide accurate results
  - Time and speciation-resolved observations in order to evaluate processes
The increase of NO$_2$ vertical column density indicates that NO$_2$ emissions increased significantly from the 2005-2007 period to the 2008-2010 period.
2013 Summer Field Study

• An intensive air quality monitoring field study, including aircraft and special surface measurements, was carried out in the AOSR during summer 2013 to better understand impacts from oil sands developments and evaluate model process representation.

• Environment Canada’s GEM-MACH AQ modelling system was set up at model grid spacing down to 2.5 km to conduct nested AQ modeling to provide forecast guidance for airborne laboratory flight planning and later post-study analysis.

• Accurate emissions information inputs will improve the AQ modeling.
Aerial Overview of the Study Area

- oil sands Minable Area
  ~ 4,800 km²

- active mining area

- mine pits

- tailing ponds

- upgrader facilities (3)

Li et al, 2014, AGU
Nested Domains: 3 Levels of Nesting for Environment Canada GEM-MACH AQ Model

- Continental GEM-MACH North American 10-km resolution forecast domain
- Experimental GEM-MACH 10-km resolution oil sands domain
- Experimental GEM-MACH 2.5-km resolution oil sands domain

Study Area
Major Accomplishments

• Review and select the most robust and relevant information from existing inventories, and measurements from CEMS and during abnormal operating conditions

• Allocation of emissions *within* each Oil Sands facility using spatial surrogates

• Creation of monthly profiles based on statistics of mined oil sands and bitumen production for temporal disaggregation of annual emissions to each month

• VOC chemical speciation based on source type: mine face, plant, and tailing ponds

• Potential improvements to emissions estimates and emissions processing for air quality modeling based on aircraft observations
As part of the work, several different sources of information were reviewed and compared in order to build an improved data base:

- The Cumulative Environmental Management Association (CEMA) Air Working Group Emission Inventory
- The Lower Athabasca Regional Plan (LARP) Emissions Inventory
- Environmental Protection and Enhancement Act (EPEA) Approvals Emissions Data
- The Alberta Industrial Air Emissions Survey
- The Alberta Air Emissions Inventory (AAEI)
- The Canadian National Pollutant Release Inventory (NPRI)
- The Canadian Air Pollutant Emissions Inventory (APEI), including NPRI for facility reported data along with emission estimates for other sources
- The Wood Buffalo Emissions Inventory
- Two EPEA Approval Applications / Environmental Impact Assessments inventories (Frontier and Voyageur South)
Different spatial coverage

<table>
<thead>
<tr>
<th>Inventory Name</th>
<th>Geographic Scope</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEMA Inventory</td>
<td>Lower Athabasca Region</td>
</tr>
<tr>
<td>LARP Inventory</td>
<td>Lower Athabasca Region</td>
</tr>
<tr>
<td>EPEA Approvals</td>
<td>Entire Province</td>
</tr>
<tr>
<td>Alberta Industrial Air Emissions Survey</td>
<td>Entire Province</td>
</tr>
<tr>
<td>Alberta Air Emissions Inventory</td>
<td>Entire Province</td>
</tr>
<tr>
<td>National Pollutant Release Inventory</td>
<td>All of Canada</td>
</tr>
<tr>
<td>Air Pollutant Emissions Inventory</td>
<td>All of Canada</td>
</tr>
<tr>
<td>Wood Buffalo Emissions Inventory</td>
<td>Wood Buffalo Environmental Association (WBEA) Airshed Zone</td>
</tr>
<tr>
<td>EPEA Approval Application &amp; EIA (various inventories)</td>
<td>Variable, project specific</td>
</tr>
</tbody>
</table>
## Emissions Inventories Review (3)
### Different levels of detail

<table>
<thead>
<tr>
<th>Inventory Name</th>
<th>Level of Detail</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEMA Inventory</td>
<td>Release point (e.g., stack)</td>
</tr>
<tr>
<td>LARP Inventory</td>
<td>Release point (e.g., stack)</td>
</tr>
<tr>
<td>EPEA Approvals</td>
<td>Facility totals, some release point</td>
</tr>
<tr>
<td>Alberta Industrial Air Emissions Survey</td>
<td>Release point (e.g., stack)</td>
</tr>
<tr>
<td>Alberta Air Emissions Inventory</td>
<td>Combination of release point, facility total, regional area &amp; mobile sources</td>
</tr>
<tr>
<td>National Pollutant Release Inventory</td>
<td>Facility total, some source categories</td>
</tr>
<tr>
<td>Air Pollutant Emissions Inventory</td>
<td>NPRI + UOG + sector totals of area and mobile sources for the whole province/region</td>
</tr>
<tr>
<td>Wood Buffalo Emissions Inventory</td>
<td>Release point (e.g., stack)</td>
</tr>
<tr>
<td>EPEA Approval Application &amp; EIA (various inventories)</td>
<td>Release point (e.g., stack)</td>
</tr>
</tbody>
</table>
This table shows the variation across different inventories, which were constructed for different purposes and different inventory years. As a result, agreement on totals across inventories is not expected.
Criteria Air Contaminants (CAC) quantification profile

- Sorted by decreasing level of estimation accuracy

Quantification of CAC emissions from non-conventional O&G, 2008 ESRD Industrial Survey
Emissions Inventories Review (5)

CEMS measurements and emissions under abnormal conditions

- CEMS have been installed on some of the large stacks to measure SO$_2$ and/or NO$_x$ emissions
- Hourly SO$_2$ and/or NO$_x$ emissions measured by 20 CEMS at four Athabasca oil sands facilities for August and September, 2013 were made available courtesy of Alberta Environment and Sustainable Resource Development
- Additional SO$_2$ emissions during abnormal operating conditions through flaring stacks can be more than one order of magnitude larger than those during normal conditions.

CNRL SO$_2$ Emissions (kg/hr)
JOSM Emissions Inventory Requirements for AQ Modeling

- Representation of 2013 emissions (Aug-Sept 2013 field study)
- Pollutants: CO, NO\textsubscript{X}, SO\textsubscript{2}, PM\textsubscript{10}, PM\textsubscript{2.5}, NH\textsubscript{3}, VOCs
- Detailed stack-level emissions for the study area
- Detailed non-point source emissions for the study area
- Industrial point sources outside the study area
- Industrial and non-industrial area and mobile sources for the entire modelling domain
- Appropriate chemical speciation and temporal profiles, up-to-date spatial surrogates
- New Source Classification Codes (SCCs) if required
Inventory selection

- Within study area:
  1) CEMS SO$_2$ and/or NO$_X$ emissions if available
  2) 2010 CEMA inventory with VOC emissions scaled up to 2010 NPRI levels

- Outside study area:
  1) 2010 APEI inventory

Gap Filling

- 2013 NPRI used to fill gaps in the study area, such as:
  1) Emissions from the new Imperial Kearl facility
  2) NH$_3$ emissions
  3) Fugitive dust emissions

- Included flaring SO$_2$ emissions during abnormal operating conditions if available
Nine New Source Classification Codes Were Created

<table>
<thead>
<tr>
<th>SCC code</th>
<th>SCC description</th>
</tr>
</thead>
<tbody>
<tr>
<td>23100000EX</td>
<td>Extraction-only plants</td>
</tr>
<tr>
<td>23100000UP</td>
<td>Integrated extraction and upgrading plants</td>
</tr>
<tr>
<td>23100000IS</td>
<td>In situ plants</td>
</tr>
<tr>
<td>23250000MF</td>
<td>Mine face</td>
</tr>
<tr>
<td>2501000P01</td>
<td>Tailings pond(s) for Shell Muskeg River and Imperial Kearl sites</td>
</tr>
<tr>
<td>2501000P02</td>
<td>Tailings pond(s) for CNRL Horizon site</td>
</tr>
<tr>
<td>2501000P05</td>
<td>Tailings pond(s) for Syncrude Aurora North site</td>
</tr>
<tr>
<td>2501000PSU</td>
<td>Combined tailing pond for Suncor Millennium site</td>
</tr>
<tr>
<td>2501000PSY</td>
<td>Combined tailing pond for Syncrude Mildred Lake site</td>
</tr>
</tbody>
</table>
Spatial Allocation of Emissions

- It is not appropriate to treat emissions from each facility as point sources because of the large size (~10 km) of the facilities and the 2.5 km model resolution.
- Spatial surrogates have been developed to allocate emissions *within* each facility to model grid cells.
Operating Mine Pit Locations in 2010

Spatial Surrogates Generated for Distributing Mine-Related Emissions
Existing Tailings Pond Locations in 2010

Spatial Surrogates Generated for Distributing Tailings Pond Emissions

Note: The same as the mine surrogate, tailing pond surrogate is facility specific.
Existing Plant Locations in 2010

Spatial Surrogates Generated for Distributing Plant Emissions

Note: The same as the mine surrogate, plant surrogate is facility specific.
Updates to Spatial Surrogates for 2013 Field Study Based on 2013 Satellite Images

New Imperial Kearl Mine
Temporal Disaggregation of Emissions

- Inventories give annual totals, but hourly emissions are required by model.
- Monthly temporal profiles were generated based on 2013 monthly statistics of mined oil sands (for mine fleet emissions) and bitumen production for each facility (for plant emissions). Weekly and diurnal profiles are assumed uniform under normal operating conditions.

- Mined oil sands vary from month to month and from facility to facility.
- Bitumen production statistics have a similar trend (not shown).
Temporal Disaggregation of Emissions

Monthly profiles created for off-road fleet (top) and plant emissions (bottom)

- Temporal data sources: monthly “mined oil sands” for the off-road fleet emissions and “bitumen production” for plant emissions.

- The two monthly profiles generally resemble each other.

- There is about two months lag from extraction (March) of oil sands to significant bitumen production (May) for the new Kearl Mine facility.
VOC Chemical Speciation

- Solvents used to extract crude bitumen from oil sands varies from facility to facility.
- VOC emitted from different tailings ponds within the same facility can be different too.
- Detailed VOC species (~300) are reported to NPRI by facilities under *Canadian Environmental Protection Act*. However, it is a facility total.
- The CEMA inventory, on the other hand, has proposed VOC speciation profiles for various types of plants and tailings ponds.
- Therefore VOC speciation profiles used were based on CEMA profiles.
## VOC Emitted from Plants

<table>
<thead>
<tr>
<th>VOC Species</th>
<th>Integrated Extraction and Upgrading Plants (UPGRD)</th>
<th>Extraction only Plants (EXTRC)</th>
<th>In situ Plants (INSTU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paraffins carbon bond (C-C)</td>
<td>70.7</td>
<td>89.9</td>
<td>96.7</td>
</tr>
<tr>
<td>Terminal olefin carbon bond (R-C=C)</td>
<td>5</td>
<td>0.45</td>
<td>0</td>
</tr>
<tr>
<td>Toluene and other monoalkyl aromatics</td>
<td>5.7</td>
<td>0.13</td>
<td>0.12</td>
</tr>
<tr>
<td>Xylene and other polyalkyl aromatics</td>
<td>9.9</td>
<td>0.034</td>
<td>0.041</td>
</tr>
<tr>
<td>Formaldehyde</td>
<td>0.033</td>
<td>0.001</td>
<td>0</td>
</tr>
<tr>
<td>Acetaldehyde</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ethene</td>
<td>0.16</td>
<td>0.023</td>
<td>0</td>
</tr>
<tr>
<td>Isoprene</td>
<td>0.0041</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Methanol</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ethanol</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Internal olefin carbon bond (R-C=C-R)</td>
<td>0.62</td>
<td>0.29</td>
<td>0</td>
</tr>
<tr>
<td>Propionaldehyde and higher aldehydes</td>
<td>0.17</td>
<td>7.4</td>
<td>0</td>
</tr>
<tr>
<td>Terpene</td>
<td>1.3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>TOTAL</td>
<td>93.5871</td>
<td>98.228</td>
<td>96.861</td>
</tr>
</tbody>
</table>

* Based on limited speciation profiles at representative facilities
## VOC Chemical Speciation (CEMA)

### VOC Emitted from Tailings Ponds

<table>
<thead>
<tr>
<th>Solvent Type (If available)</th>
<th>Paraffinic Hydrotreated Naphtha</th>
<th>Untreated Naphtha</th>
<th>N/A</th>
<th>N/A</th>
<th>N/A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tailings Type/ VOC species</td>
<td>Primary / Secondary (POND1)</td>
<td>Primary / Secondary (POND2)</td>
<td>Primary / Secondary (POND4)</td>
<td>Primary (POND3)</td>
<td>InPit (INPIT)</td>
</tr>
<tr>
<td>Paraffins carbon bond (C-C)</td>
<td>54.42</td>
<td>51.33</td>
<td>62.58</td>
<td>55.05</td>
<td>63.31</td>
</tr>
<tr>
<td>Terminal olefin carbon bond (R-C=C)</td>
<td>0.47</td>
<td>0.3</td>
<td>7.15</td>
<td>2.42</td>
<td>1.02</td>
</tr>
<tr>
<td>Toluene and other monoalkyl aromatics</td>
<td>0.42</td>
<td>0.71</td>
<td>6.31</td>
<td>10.82</td>
<td>15.94</td>
</tr>
<tr>
<td>Xylene and other polyalkyl aromatics</td>
<td>40.11</td>
<td>44.7</td>
<td>22.46</td>
<td>20.18</td>
<td>14.64</td>
</tr>
<tr>
<td>Formaldehyde</td>
<td>0.05</td>
<td>0</td>
<td>0.079</td>
<td>0.066</td>
<td>0.1</td>
</tr>
<tr>
<td>Acetaldehyde</td>
<td>0.0075</td>
<td>0</td>
<td>0</td>
<td>0.014</td>
<td>0.05</td>
</tr>
<tr>
<td>Ethene</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.0025</td>
</tr>
<tr>
<td>Isoprene</td>
<td>0.019</td>
<td>0</td>
<td>0</td>
<td>0.0023</td>
<td>0.0008</td>
</tr>
<tr>
<td>Methanol</td>
<td>0.23</td>
<td>0</td>
<td>0</td>
<td>0.89</td>
<td>0.00041</td>
</tr>
<tr>
<td>Ethanol</td>
<td>0.0046</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.00033</td>
</tr>
<tr>
<td>Internal olefin carbon bond (R-C=C-R)</td>
<td>0.37</td>
<td>0.26</td>
<td>1.04</td>
<td>1.49</td>
<td>0.15</td>
</tr>
<tr>
<td>Propionaldehyde and higher aldehydes</td>
<td>0.24</td>
<td>0.036</td>
<td>0.017</td>
<td>0.24</td>
<td>1.18</td>
</tr>
<tr>
<td>Terpene</td>
<td>0.64</td>
<td>0.11</td>
<td>0</td>
<td>0.15</td>
<td>0.49</td>
</tr>
<tr>
<td>TOTAL</td>
<td>96.98</td>
<td>97.45</td>
<td>99.64</td>
<td>91.3</td>
<td>96.8</td>
</tr>
</tbody>
</table>

*Mostly based on surface flux chamber measurements conducted at representative facilities*
AQ Model Forecast for Flight Planning during the Field Study

104 km length, 100 km radius: 20 minutes + 3 minutes turn time per leg. 4 cross-sections = 92 minutes

Centroid: 57°51'5.18" N 111°32'54.31" W
= 57° 51.0863333° N, 111° 32.90516667° W

105 km length, 50 km radius: 20 minutes + 3 minutes turn time per leg.
3 cross-sections = 69 minutes each (do twice).
Aircraft Campaign During the 2013 Summer Study

• 22 flights (84 hours airborne) were flown during Aug. 13 – Sept. 7 period in support of the following goals:
• To provide data for satellite retrieval validation
• To understand the transport and transformation of primary pollutants
• To quantify emissions of criteria air contaminants (CACs) and other air pollutants through ambient air measurements in the oil sands region
• To evaluate and improve a high-resolution air quality model – GEM-MACH model
Emissions Estimation Based on Aircraft Observations
Top-down Emission Rate Retrieval Algorithm (TERRA: Gordon et al., 2015)

1) Aircraft measured high SO2 emissions during abnormal operation event on Aug. 20
2) Primary results showed that uncertainty of the TERRA estimation is within 20% of observed / reported emissions.
3) Detailed VOC species observed by aircraft will also be used to evaluate current VOC speciation for AQ modeling
Conclusions

• This work has resulted in an improved emissions inventory in the study area for the JOSM project
• Emissions inventory analysis is an important step for emissions processing
• For large facilities, spatial allocation of emissions within a facility is necessary for high-resolution modeling
• The inventory used should match the modelling period as closely as possible, particularly for the Oil Sands area due to its rapid development
• Aircraft observations can provide valuable information for top-down emissions estimation
• Work is ongoing to further improve the inventory being used for GEM-MACH modelling for the oil sands
THANK YOU