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Spatial and temporal variation of CO over Alberta using measurements from satellite, aircrafts, and ground stations

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Abstract

Alberta is Canada's largest oil producer and its oil sand deposits comprise 30 % of the world's oil reserves. The process of bitumen extraction and upgrading releases trace gases and aerosols to the atmosphere. In this study we present satellite-based analysis to explore, for the first time, various contributing factors that affect tropospheric carbon monoxide (CO) levels over Alberta. The multispectral product that uses both near-infrared (NIR) and the thermal-infrared (TIR) radiances for CO retrieval from the Measurements of Pollution in the Troposphere (MOPITT) are examined for the 12 year period from 2002–2013. Moderate Resolution Imaging Spectroradiometer (MODIS) thermal anomaly product from 2001 to 2013 is employed to investigate the seasonal and temporal variations of forest fires. Additionally, in situ CO measurements at industrial and urban sites are compared to satellite data. Furthermore, the available MOZAIC/IAGOS (Measurement of Ozone, Water Vapor, Carbon Monoxide, Nitrogen Oxide by Airbus In-Service Aircraft/In service Aircraft for Global Observing System) aircraft CO profiles (April 2009–December 2011) are used to validate MOPITT CO data. The climatological time curtain plot and spatial maps for CO over northern Alberta indicate the signatures of transported CO for two distinct biomass burning seasons, summer and spring. Distinct seasonal patterns of CO at the urban site *s* (Edmonton and Calgary cities) point to the strong influence of traffic. Meteorological parameters play an important role on the CO spatial distribution at various pressure levels. Northern Alberta shows stronger upward lifting motion which leads to larger CO total column values while the poor dispersion in central and south Alberta exacerbate *s* the surface CO pollution. Inter-annual variations of satellite data depict a slightly decreasing trend for both regions while the decline trend is more evident from ground observations, especially at the urban sites. MOPITT CO vertical averages and MOZAIC/IAGOS aircraft profiles were in good agreement within the standard deviation at all pressure levels. There is consistency between the time evolution of high CO episodes monitored by satellite and ground measurements and the fire frequency peak time which implies

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that biomass burning has affected the tropospheric CO distribution in northern Alberta. These findings have further demonstrated the potential use of MOPITT V5 multispectral (NIR+TIR) product for assessing a complicated surface process.

1 Introduction

Canada's crude oil reserves represent the world's 3rd largest after Saudi Arabia and are currently the world's 7th largest producer of crude oil (CAPP, 2012). Alberta is Canada's largest oil producer and its oil sands deposits comprise 30 % of the world's oil reserves (Kean, 2009). Alberta's oil sands deposits are located in three regions: Athabasca, Peace River and Cold Lake. The Athabasca oil sands region (AOSR) (Fig. 1) contains most of the oil sands reserves. About 20 % of the deposits in the Athabasca region are shallow (< 75 m deep) and hence can be surface mined. The bitumen contained within the sand is extremely heavy crude oil, requiring heat or solvents to extract it from the sand (Alberta Environment, 2012). The surface mining of the bitumen utilizes a hot water process for extraction, which releases SO_2, H_2S and light hydrocarbons as well as CO_2 and CO (Strausz et al., 1977). After extraction, water and solids are removed from bitumen using solvents/diluents such as naphtha (Siddique et al., 2007) and Paraffins (Siddique et al., 2006) which are also used to decrease bitumen's viscosity so that it can be ready for processing. Deeper deposits are not recoverable by surface mining: in situ recovery methods such as steam injection are needed for extraction. Larger amounts of natural gas are required to upgrade the bitumen before it is sent through pipelines (NEB, 2013). Thus the rapid expansion of oil extraction, and massive energy requirements to extract and upgrade the bitumen, led to numerous environmental concerns, particularly on air quality (Timoney and Lee, 2009) and hence an environmental monitoring program that measures the ambient air quality is needed. Air monitoring in Alberta is carried out through airshed associations that were launched as non-profit societies under the umbrella of the Clean Air Strategic Alliance (CASA). Air quality in the AOSR is monitored locally by the Wood Buffalo

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Environmental Association (WBEA), which is a multi-stakeholder organization (WBEA, 2013). In addition to the existing continuous air quality monitoring network in Alberta, independents studies were conducted to investigate the impact of the oil sands mining operations on the air quality over Alberta (e.g. Bytnerowicz et al., 2010; Jacob et al., 2010; Simpson et al., 2010; Howell et al., 2014). Recent studies of aerosol and trace gas emissions have been carried out in summer 2008 when the NASA DC-8 and P-3B research aircraft were deployed at the Canadian Forces Base Cold Lake in Alberta, Canada (Jacob et al., 2010). Their work reported significantly elevated levels of trace gases (CO_2, CH_4, CO, NO, NO_2, NO_y, SO_2 and 53 VOCs) above background levels (Simpson et al., 2010). However, these data are limited in spatial coverage as they reflect local air quality and cannot provide information about the overall regional air quality. A complementary approach to surface and aircraft measurements is satellite-based monitoring which can provide large spatial coverage and making measurements over extended periods of time, allowing the study of the impact of intense emission sources on regional and global scale air quality. Over the last decade, satellite remote sensing of trace gases and aerosols for air quality applications has progressed (Martin, 2008). Despite the emerging importance of using satellite in air quality applications, there are no researches using them over Alberta until 2012, when McLinden et al. (2012) employed the Ozone Monitoring Instrument (OMI) instrument for NO_2 and SO_2 assessment over the AOSR. They presented high-resolution maps that revealed distinct increases above background levels for both species over the area of intensive surface mining. In addition, they showed that NO_2 is increasing at a rate of 11 % $year^{-1}$ which is generally consistent with the annual rate increase of bitumen production. Accordingly, further study to characterize more trace gases and aerosols that are emitted from various natural and anthropogenic sources in Alberta is required.

Beside oil sands operations, Alberta has other anthropogenic sources, such as combustion of fossil fuels and various industrial processes which emit 428 692.5 t of CO in 2012 (EC, 2012). Additionally, natural emissions such as boreal forest fires are a major source of CO. Canada boreal forest fires in summer influence the carbon cycle (Pre-

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ston and Schmidt, 2006), climate (Amiro et al., 2001), and air quality (Colarco et al., 2004; Pfister et al., 2006). The fire frequency at high latitudes (> 55° N), is expected to increase (Gillett et al., 2004; Girardin, 2007) as a result of global warming (Stocks et al., 1998; Flannigan et al., 2005) which is accompanied by increased dryness and temperature (Marlon et al., 2008).

One of the most important trace gases emitted from anthropogenic pollution and open biomass burning, is CO. CO can also, it can be produced from photochemical oxidation of CH_4 and non-methane hydrocarbons (Novelli et al., 1998; Duncan et al., 2007). CO plays a critical role in the tropospheric chemistry where it is the dominant sink of the hydroxyl radical (OH), which is the major oxidizing agent in the troposphere. It has also significant impacts on regional air quality where it can be a precursor to photochemical ozone smog in areas with suficient NO_x (Ridley et al., 1992). Additionally, CO was recognized as an important indirect greenhouse gas that could have an effect on global climate (Daniel and Solomon, 1998). With a relatively long life-time (the global average CO lifetime is about 2 months), CO is an excellent tracer for tropospheric transport processes (Pétron, 2004) and plumes from strong emission sources that are extending great distances. Fortunately, CO is one of the few tropospheric gases that can be successfully monitored from space at the present time. It has been measured by the Measurements of Pollution in the Troposphere (MOPITT) instrument on NASA's Terra satellite, creating a global record from 2000 to the present. Thus, the long term record of MOPITT data allows the investigation of the inter-annual and spatial variability of tropospheric CO air quality. Accordingly the current study aims to address the general features of the overall CO loading over Alberta using MOPITT data. The major source contributions of CO and their impacts on temporal and spatial variability will be examined through the use of MOPITT and Moderate Resolution Imaging Spectroradiometer (MODIS) sensors, meteorology and ground level measurements. This work is the first study to explore various contributing factors that affect tropospheric CO levels over Alberta using satellite remote sensing observations. The data and methods used in the study are described briefly. Climatological spatial distribution and time-altitude

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profiles of MOPITT CO over Alberta are presented and compared with aircraft CO profiles and ground-level measurements. The contribution of forest fires to CO levels in the AOSR are analysed using MODIS fire counts analysis.

2 Data and methods

This study uses data from two satellite instruments, MODIS (available from https://earthdata.nasa.gov/data/near-real-time-data/firms) and MOPITT V5J (available from ftp://l5eil01.larc.nasa.gov/MOPITT/MOP02J.005) coupled with ground measurement data (available from http://www.casadata.org/). Fort McMurray, Edmonton, and Calgary areas are chosen for analysis where the former represents industrial oil sand region and the latter represents an urban region (see Table 1).

2.1 Satellite data

2.1.1 MOPITT

The MOPITT instrument on board Terra spacecraft is specifically designed to measure CO profiles and total columns (Drummond, 1992). It takes about 3 days for near-complete global coverage with a horizontal resolution of 22 km × 22 km at nadir (Deeter et al., 2003). MOPITT has a unique feature compared to other tropospheric CO satellite instruments, as it measures CO simultaneously in both the thermal infrared (TIR) band (4.7 µm) and the near-infrared (NIR) band (2.3 µm). The NIR observations mainly provide information about the CO total column whereas TIR radiances are often most sensitive to CO in the middle and upper-troposphere. In this study we used the MOPITT multispectral product that exploits both channels (TIR+NIR) which has been shown to have higher sensitivity to CO in the lower troposphere (Worden et al., 2010; Deeter et al., 2011, 2012; Jiang et al., 2013). MOPITT V5 data have been recently validated using in situ CO profiles measured from aircraft (Deeter et al., 2013). Only daytime MO-

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PITT retrievals were used in this study because they have better information content than nighttime data (Deeter et al., 2010).

2.1.2 MODIS thermal anomaly products

MODIS sensors are located on the Terra and Aqua satellite platforms. They were designed to offer a broad range of information about land, oceanic, and atmospheric conditions (Kaufman et al., 1998a and Masuoka et al., 1998). They detect fires globally on a daily basis at 1 km spatial resolution. The fire detection algorithm has been described by Kaufman et al. (1998b) and Giglio et al. (2003). In this study we used the Collection 5.1 Terra and Aqua MODIS MOD1/MYD14 product from November 2000 (Terra) and July 2002 (Aqua) through December 2012. Each fire pixel is associated with a confidence limit parameter to specify the quality of the data which range from 0 to 100 % (Giglio, 2007). The threshold limit for fire pixel confidence that is used in this study is 30 %, which is a heuristic measure of the radiometric contrast between a fire pixel and its immediate non-fire neighborhood, with extra penalties imposed near potential false alarm sources such as cloud edges and coastline (Giglio et al., 2003). We used the MODIS fire data in the shape file format in order to use them in geographic information system (GIS) maps. Data were obtained from the Land Atmosphere Near-real time Capability for EOS (LANCE) system operated by the NASA/GSFC/Earth Science Data.

2.2 CASA ground measurements

CASA Data Warehouse (www.casadata.org) is a central repository for ambient air quality data collected in Alberta. The in situ measurements of surface CO were recorded at nine monitoring stations in the study region. CO is monitored continuously either by non-dispersive infrared photometry or gas filter correlation (Alberta Environment, 2013).

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2.3 MOZAIC/IAGOS (Measurement of Ozone, Water Vapor, Carbon Monoxide, Nitrogen Oxide by Airbus In-Service Aircraft/In service Aircraft for Global Observing System) Aircraft Measurements

IAGOS (formerly MOZAIC) instruments onboard commercial aircraft since August 1994, aim to sample the tropospheric gases with high vertical resolution over about 50 airports (Marenco et al., 1998). CO has been monitored since 2001 using the infrared CO analyzer (Model 48CTL from Thermo Environmental Instruments, USA) with a precision of ±5 ppbv (Nedelec et al., 2003). Data are available at http://www.iagos.org.

2.4 Meteorological data and HYSPLIT trajectories

The HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) model Version 4 was used to generate air mass backward trajectories. It is the latest version of an integrated system for computing air parcel trajectories, dispersion and deposition simulations. The model calculates the trajectories using the Global Data Assimilation System (GDAS) meteorological dataset which has been operated by National Centers for Environmental Prediction (NCEP) (Rolph and Rolph, 2013; Draxler et al., 2013). Trajectory calculation is carried out by time integration of the position of an air parcel as it is transported by the 3-D winds (Draxler and Hess, 1998). Data of mean monthly omega for the study period were taken from the National Oceanic and Atmospheric Administration (NOAA) Climate Data Assimilation System I, based on the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis Project. The NCEP/NCAR global re-analysis meteorological dataset is described in detail by Kalnay et al. (1996).

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3 Results and discussion

3.1 Climatological spatial distribution of MOPITT CO over Alberta

Figure 2 shows the seasonally averaged distribution of MOPITT CO total column measurements over Alberta for the period March 2002 to December 2013. The symbol F, E and C represent Fort McMurray, Edmonton and Calgary cities, respectively. Data are gridded at $0.25^{\circ} \times 0.25^{\circ}$ resolution. Figure 2 depicts the seasonal climatological maps for CO total columns. High CO loadings extended from the North East to North West of Alberta in all seasons except in winter (December–February) where the spatial variations are less prominent. CO total columns illustrate remarkable maximum values in the northeast area (oil sand area) in the spring (March–May) where the CO total column ranges are $2.5\text{–}2.75 \times 10^{18}$ molecules cm^{-2}. Additionally, it is apparent that summer (June–August) and fall (September–November) seasons displayed minimum CO loading, especially in the center and south of Alberta.

The spatial distributions of CO mixing ratios at the surface level (Fig. 3) reveal distinct enhancements, covering south east Alberta in winter with CO mixing ratios of 180–200 ppb. In the spring the CO mixing ratios are generally high in the whole of Alberta. The summer season demonstrated relatively high surface CO concentrations (140–160 ppb) north of Fort McMurray, although it shows minimum levels for the rest of Alberta, while the fall season illustrates similar spatial distribution. Thus, the spatial distributions of surface CO especially in spring and winter indicates a different pattern than the CO total column (Fig. 2) for the same period. To assist in the interpretation of the results, the vertical velocity (Omega) which is defined as change of pressure with time is analyzed. The spatial distributions of averaged Omega ($\mathrm{d}p/\mathrm{d}t$) for 2002–2013 at pressure level 850 mb for four seasons are depicted in Fig. 4. They demonstrate upward movements of air mass in the area of northeast and southwest of Alberta as indicated by negative values. This suggests that the CO emissions are uplifted, raising the CO total column values in the north area. Conversely, downward movements (positive values) are recorded in the center and south east Alberta allowing subsidence of

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CO emissions as conditions are favorable. Therefore, there is a general consistency between the climatological maps of Omega and the CO spatial distributions where the CO total columns shows remarkable enhancements in the north while the surface CO experiences elevated values in the south area. This highlights the important role of meteorological parameters on ambient air quality.

The southwestern area of Alberta exhibits minimum CO levels, which are less than 1.5 molecule cm^{-2} and 60 ppb for CO total column and surface concentration (Figs. 2 and 3), respectively. Alberta has a varied topography, from mountain peaks along the western border, to lowland areas in northeastern Alberta. It follows, then, that topographical features influence air quality – mountainous regions with little population contribute to background conditions of CO resulting in the lowest CO concentrations in the Southwest Alberta.

The main sources of CO in the atmosphere are combustion processes and photochemical oxidation of hydrocarbons (Novelli et al., 1998; Duncan et al., 2007). Hence, it is assumed that CO spatial variations in northern Alberta are associated with oil sands industrial activities because of combustion and photoxidation of hydrocarbons. It is reported that oil sands industry consumption of natural gas was 17×10^6 m^3 day^{-1} in 2003 and is expected to increase to 40–45 million m^3 day^{-1} in 2015 (NEB, 2013).

The extracted bitumen is then upgraded in upgraders located north of Fort McMurray as well as downstream industrial centers such as the industrial heartland in Fort Saskatchewan (north east Edmonton), Alberta. A small fraction of diluent used in bitumen extraction and transport is emitted to the atmosphere (Siddique et al., 2006). The diluents are mainly aromatic and aliphatic hydrocarbons (Siddique et al., 2007). As reported in earlier studies, the measured CO on 10 July 2008, as part of Arctic Research of the Composition of the Troposphere from Aircraft and Satellites (ARCTAS) mission, showed a strong correlation with alkanes, aromatics and cycloalkanes that are associated with direct emissions from the oil sands and/or diluent (Simpson et al., 2010). Furthermore, the timing, distribution of other sporadic sources such as fires, and the ef-

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fects of large-scale transport have a substantial influence on the spatial discrepancies of CO.

3.2 Time-altitude MOPITT CO

To gain further insight about the impact of various emission sources on CO levels, temporal climatology of 12 years for Fort McMurray (including the oil sand area), Edmonton, and Calgary areas are calculated. The monthly mean CO profiles using all the available MOPITT data between March 2002 and December 2013 are used for altitude/month contours for the two regions (Fig. 5). The vertical profiles of MOPITT CO are retrieved on only 10 altitude levels (surface, 900, 800, 700, 600, 500, 400, 300, 200, 100 hPa), so levels in between have been linearly interpolated. However, earlier studies of the averaging kernels indicated that there are effectively not more than two independent pieces of information (1.4–2) in the vertical profiles retrieved by MOPITT, with more sensitivity to the middle troposphere (Deeter et al., 2007; Worden et al., 2010).

Generally, all regions demonstrate the same profile structure where CO mixing ratios are higher at low altitudes (high pressure) than high altitudes (low pressure). At Edmonton and Calgary, vertical CO profile exhibits significant elevated levels in winter and spring, occurring in February and April with maximum mixing ratios of 175 ppb at low altitude levels ($\leq$ 800 hPa), while it shows minimum mixing ratios in summer. This pattern is consistent with the general seasonal cycle of CO in Northern Hemisphere (NH). Edwards et al. (2004) analyzed CO variability from the Terra MOPITT satellite in NH and their result showed peak values in the early spring due to fossil fuel burning for heating and increased power requirements. The wintertime CO emissions persist for several weeks after the emissions themselves have ceased causing high CO concentrations which are detected in early spring. In fact, the seasonal cycle of CO loading is driven primarily by the balance of emissions and photochemical production, and destruction by hydroxyl radical (OH) (Novelli et al., 1998). During the summer months under conditions of high solar illumination, OH is produced mainly through O_3 pho-

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tolysis and subsequent reaction with H_2O which accounts for strongest sink of CO in summer. Thus the main (90 %) CO loss is caused by OH oxidation, followed by dry deposition (Thompson, 1992).

Although both Calgary and Edmonton represent urban pollution, Calgary CO concentrations show lower values in winter. Different air masses and weather systems influence Alberta, and it is likely that these have a significant impact on air quality. Southwestern Alberta indicates a complex and non-uniform spatial pattern of chinook frequency in winter that is associated with warmer temperature anomaly and strong westerly winds. In particular, Calgary is expected to experience Chinook winds more than Edmonton since chinook effects are strongest in southern portions of Alberta. Accordingly, Calgary is more affected by westerly winds that carry fresh air from mountain and hence it may contribute in pollution dilution (Cullen and Marshall, 2011). Additionally, Calgary has less industrial development than Edmonton.

The seasonality in the Fort McMurray area is progressively less pronounced, where there is a marked increase of CO loading in summer (looks more like April and May), especially at low altitude levels (≤ 800 hPa). However, because the OH loading is higher in summer than the springtime, the CO peak does not persist long and decline rapidly. Simpson et al. (2011) calculated backward trajectories for ten days started on 10 July 2008 over the Athabasca surface mines (northeast Alberta) as part of the summer deployment of the ARCTAS field mission. The aircraft flew over both boreal forest and industrial land including tailings ponds and upgrader facilities. Then the aircraft flew on a clean air area further south of the oil sands area. The ten-day backward trajectories for the area south of the oil sands (by one degree) and clean areas revealed that the air masses are transported at the aircraft's pressure level from the west and not from oil sands mines to the north. Consequently, summer CO increments can be attributed to the other sporadic sources such as forest fires. Thus, the forest fire emissions will be discussed in Sect. 3.5. Furthermore the winter/spring levels over Fort McMurray area start to peak late in April and May with maximum mixing ratios of 135–155 ppb (≤ 800 hPa). Figure 5 illustrates higher CO mixing ratios at low altitude levels

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(≤ 800 hPa) over Edmonton and Calgary areas than Fort McMurray area, especially in winter and spring that point out the significance of the non-industrial sources (e.g. vehicle emissions). It is reported that, CO emissions from mobile sources (e.g. transportation emissions) over Alberta in 2011 was about 900 000 t which is about 60 % of the total CO emissions (1.5 million t) (Environment Canada, 2011).

For all locations, CO mixing ratios in spring exhibit greater values at higher altitudes (pressures less than 700 hPa) compared to other seasons. This could be attributed to seasonal variations in deep convection, which lofts surface emissions into the upper troposphere (e.g., Duncan et al., 2007; Jiang et al., 2007; Liu et al., 2010; Livesey et al., 2013). This is further confirmed by monthly omega averages (2002–2013) at 700 hPa (Fig. 6) which indicate that the vertical mixing is more usual in May and June where omega averages range from −0.02 to −0.01.

Although monthly CO mixing ratios over Edmonton and Calgary areas are higher at lower altitudes, the CO total column monthly averages for all regions are comparable (not shown). This indicates that northern Alberta is affected more by CO plumes transported vertically above planetary boundary layer (PBL) where cities such as Edmonton and Calgary are more influenced by local emissions confined in the PBL which is more pronounced over Edmonton area.

Figure 7 shows the 12 year time series of monthly averaged CO mixing ratios (ppb) as measured by MOPITT from January 2002 to December 2013 at the ten pressure levels over Fort McMurray, Edmonton, and Calgary areas. The white intervals indicate missing data due to calibration events, instrument problems or that the pressure at that location is less than MOPITT pressure level.

Strong seasonal cycles are seen over all regions through all the years with maximum values in springtime. The degree of repeatable seasonal variability varies by year and region: it is more pronounced over the Edmonton and Calgary areas.

CO mixing ratios show a sharp vertical gradient especially over Edmonton and Calgary areas with significantly higher values in the PBL than in the free troposphere (FT). This implies that surface emissions have a strong controlling effect on the variation

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of CO in the lower troposphere. This confinement of regional emissions in the lower atmosphere is likely due to subsidence prevailing over the area as indicated by positive values of vertical velocity 700 mb. On the other hand, the vertical gradient of CO mixing ratios over the Fort McMurray area is small and there are relatively high values at high altitudes (< 500 hPa) which may be result of transported CO from biomass burning plumes. Furthermore, CO mixing ratios of Edmonton and Calgary areas at lower altitudes are higher than Fort McMurray area during the entire period. This result indicates the significance of the anthropogenic local urban sources (e.g. transportation) compared to the industrial sources (oil sand activities). Additionally, the monthly average time series from 2002 to 2013 of CO mixing ratios over Fort McMurray area displays a secondary peak in summer while its magnitude varies from year to year. Summer CO episodes over Fort McMurray area could be a signature of polluted air parcels coming from biomass burning emissions. Accordingly, the impact of forest fire on CO levels is examined in Sect. 3.4.

The inter-annual variation of CO total column is shown in Fig. 8. The annual mean for each year is calculated and then subtracted from monthly averages of that year to show inter-annual variation. To investigate whether there is a trend; a linear regression analysis was performed to fit the observations of the monthly CO total column for Fort McMurray, Edmonton and Calgary areas. A slightly decreasing trend is identified for all regions with a rate of −1 %. The seasonal variation is evident each year with small inter-annual variability. The striking feature in 2012 is the presence of an air pollution episode in summer which is more prominent over the Fort McMurray area. CO total column variation in July over Fort McMurray area shows distinct peak among all maximums with value of 2.6×10^{18} molecules cm^{-2}. Thus in Sect. 3.5 a case study of summer 2012 is analyzed.

3.3 Comparison with MOZAIC/IAGOS aircraft CO profiles

To verify MOPITT measurements, profiles of CO MOZAIC/IAGOS aircraft on descent to or ascent from Calgary airports are exploited for comparisons. The available aircraft

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data are between April 2009 and December 2011 with a total number of 186 profiles. Because of MOPITT's temporal resolution of 2–3 days and the blockage of clouds, there are missing data in daily CO profiles and hence only the matching MOPITT and aircraft profiles in time and location are utilized. For comparison, MOZAIC/IAGOS profiles are first interpolated to the pressure level of the corresponding MOPITT retrievals.

Since the MOPITT retrieval derives CO concentration profiles by combining its radiometric observations with a priori estimates of the vertical profile of atmospheric CO, weighted by their uncertainties. the sensitivity of the retrievals to the actual concentration profiles must be considered when conducting quantitative comparisons to independent measurements (Emmons et al., 2004, 2007). The sensitivity of the MOPITT measurements to the true CO profile is represented by averaging kernels (Deeter et al., 2003). Accordingly, the interpolated aircraft profile is transformed by applying the averaging kernel and a priori profile associated with the corresponding MOPITT retrieval using Eq. (1) (Emmons et al., 2009). The transformed profiles ($\boldsymbol{x}_{\text{ret}}$) are denoted as MOZAIC/IAGOS (AK), and then they are averaged and plotted with corresponding MOPITT retrieved vertical profiles of CO as illustrated in Fig. 9a.

$$\boldsymbol{x}_{\text{ret}} = \mathbf{A}\boldsymbol{x} + (\mathbf{I} - \mathbf{A})\boldsymbol{x}_{\text{a}} \quad (1)$$

where $\boldsymbol{x}_{\text{a}}$ is the a priori CO profile, $\mathbf{A}$ is the averaging kernel, and $\boldsymbol{x}$ is the in situ CO profile.

Both aircraft and MOPITT measurements show that CO mixing ratios below 700 hPa are higher than those above 700 hPa. The vertical distributions and gradients of aircraft and MOPITT CO mixing ratios are in good agreement where their averages values match fairly well within the standard deviation at all pressure levels. However, MOPITT averages generally have positive bias in the upper troposphere where the largest differences are seen below 400 mb. Nevertheless, the comparison demonstrates the potential of using multispectral MOPITT CO data in estimating surface air quality (Worden et al., 2010; Deeter et al., 2011). The seasonal profiles of the available MOZAIC/IAGOS data are computed and displayed in Fig. 9b. They illustrate higher concentrations in

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winter for all altitudes and minimum values in summer. Additionally, spring measurements exhibited relatively high mixing ratios above ∼ 2 km. Thus the seasonal variation results are generally consistent with MOPITT results over Calgary city except that MOPITT shows the maximum in spring rather than winter. This discrepancy suggests that, winter surface emissions are more entrained in the boundary layer which exacerbates the local surface pollution, resulting in high concentrations in winter. As MOPITT's sensitivity to CO is relatively low in the boundary layer (Deeter et al., 2007) surface emission may not be captured very well. Since the meteorological conditions in spring favors lofting the emissions up (warm air is of low density), retrieved MOPITT signal at mid-troposphere can capture the enhanced CO where its sensitivity is better (Hyer et al., 2007). As a result the MOPITT data show the seasonal peak in spring rather than winter. This finding suggests that the significant influence of transported emissions on CO levels. The surface seasonal variations of CO are further confirmed by analysis of ground level measurements in the next section.

3.4 Comparison with ground measurements

In this section we consider analysis of surface CO recorded at nine monitoring stations as the in situ ground measurements are more sensitive to the boundary layer than the MOPITT CO. The elevation, exact location, starting date, and the status are presented in Table 2. The selected stations sample various anthropogenic sources of CO where Fort McMurray-Athabasca Valley is an industrial town and the other stations are urban sites (Edmonton and Calgary). The monthly-averaged time series of CO mixing ratio (ppb) at these stations are computed from 2000–2013 for comparison with MOPITT CO surface variability (Fig. 10). The availability of CASA data differs among the stations as shown in Table 1. The MOPITT data are centred at each location in a one degree grid box.

The CO temporal evolutions from all stations reveal distinct annual and inter-annual variations with a significant declining trend. The trend is more recognizable over Edmonton and Calgary cities (Fig. 10a and b) than Fort McMurray (Fig. 10c) where their

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maximum declining rate are 4.4, 5.7 and 0.6 %, respectively. Furthermore, the CO levels are much higher at the urban stations than the industrial one where their maximum concentrations are about 1000 and 500 pbb, respectively. Comparing to MOPITT, the spatial and the temporal variations of surface CO mixing ratios also experienced higher values over Edmonton city than Fort McMurray. This finding is consistent with the results of Simpson et al. (2010) that showed relatively low emitted levels of CO throughout the mining operations (north Fort McMurray area) although the CO concentrations were 48 % greater than the local background.

Additionally, it is apparent that the first 7 years (2000–2006) have larger inter-annual variations than the next years (2006–2012), especially over Edmonton and Calgary cities. In other words, the decreasing rate in the last 6 years is not as large as the first years which reflect the influence of vehicles' improvements in CO emissions (Alberta Environment, 2008). Moreover, for each city, there are discrepancies in the CO concentrations among different locations (not shown), where the central and east Calgary and central and northwest Edmonton stations exhibited the greatest values (not shown). This increase could be attributed to high traffic or industrial load at these locations which imply the substantial impact of emissions sources on ambient CO levels.

The seasonal cycle of CO is evident for all years at all stations where it is characterized by a maximum in winter (December and January) and a minimum in summer (Fig. 10). It is obvious that MOPITT CO surface data capture monthly variation as ground data except at Fort McMurray 2006. However, the magnitude of the MOPPIT surface values is less than ground data which could be attributed to the fact that the MOPITT surface values are is really the layer averages from the surface to the next level (e.g. 900 hPa) as well, as to low MOPITT surface sensitivity. Seasonal variations at Fort McMurray (Athabasca Valley station) (Fig. 10c) are different for the whole study period where a secondary peak in summer that is more pronounced in some years such as 2012 than in others. Interestingly, the summer 2012 peak value exceeds the winter values of the same year, where monthly CO mixing ratios in July 2012 were more than 300 ppb. Although MOPITT temporal resolution is about 3 days (Liu et al.,

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2005), the same feature is detected by MOPITT CO total column where the monthly July average over Fort McMurray in 2012 exceeds those of May at the same year (as shown in Fig. 8). This implies the substantial impact of a non-industrial source such as forest fires, on air quality. Consequently, it is essential to analyze the biomass burning over Alberta where it is one of the major sources of CO (Morris et al., 2006).

3.5 MODIS fire counts

To assess the impact of forest fires on CO levels, the MODIS thermal anomaly product was analyzed for 13 years (2001–2013). GIS maps were used to display the spatial distributions of active fire points using ArcGIS software version 10.1. Figure 11 illustrates the seasonal variations of fire counts for the study period over Alberta. Significant numbers of fires occurs during summer (June–August) in northern areas of Alberta extending from west to east. In the spring (February–April), large forest fires are spatially clustered in the area north of Fort McMurray as well as in central Alberta. In winter (December–February) and fall (September–November) seasons, most of the fire locations are distributed in the west and northwest areas of Alberta, especially in the fall season. Temporal analysis of fire count monthly averages for the entire period (2001–2013) demonstrates that July, June and May comprise more than 65 % of the total fire occurrence where their relative frequencies are 35, 20, and 8 %, respectively (Fig. 12a). Thus, the period of May–July is recognized to be the main biomass burning season where the largest fires occur in Northern Alberta. High pressure subsidence (a slow, sinking motion of high level air occurring in high pressure areas) and dry conditions were identified as the dominant conditions in this period of time (May–July) which cause fires where the subsiding air is warmed by compression and becomes more stable (Skinner et al., 2002; Soja et al., 2007). Inter-annual variations of seasonal fire frequency (Fig. 12b) indicate a large variability where the total number of fire counts over Alberta increased from 1959 in 2001 to 10 608 in 2012. A very distinct increase in fire frequency is observed in summer each year with peak number in 2012. Additionally, year 2011 exhibited an elevated number of fires in spring and summer where they

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exceeded 5500 fire counts for each. The overall pattern of fires is largely consistent with the seasonal and temporal variations of MOPITT CO values of northern Alberta as well as the ground level in situ measurements at Fort McMurray station. Therefore, it is suggested that, the high CO concentrations that emerge each summer in the area around Fort McMurray (northern Alberta) are mainly caused by the biomass burning of boreal forest fires. Earlier studies pointed out the significance of biomass burning on air quality where it accounts for about 30 % of the global total CO sources (Galanter et al., 2000).

To analyze in further detail the impact of fire emissions on CO levels and their transport, the variability of fire counts during July 2012 are examined as a case study. The daily time series of fire frequency in summer 2012 (not shown) illustrates a maximum number of fires on 10 and 11 July where the fire counts exceeded 1200 and the fire radiative power (FRP) reached 9510 MW. Figure 13a and b displays the MODIS Terra image combined with fire hot spots indicated by red points for 10 and 11 July 2012, respectively. It is clear that most of the red fire points are included in or headed the smoke plumes, indicating that the plumes originated from those fires.

On 10 July 2012, the air mass was transported across Alberta toward the north, then on 11 July it went from west to east at which time it splits, with part of the air mass being transported south to the Fort McMurray area. To verify the transport pathway of smoke plumes, HYSPLIT forward trajectories analyses were performed for 10 July 2012 for a 48 h period (Fig. 14a). The starting conditions for these analyses included three fire point locations chosen from the MODIS fire data. The blue circles in the trajectories represent time interval of 6 h. Analyses were done for 500, 1000, and 2000 m heights, and it seems that the plumes stayed in the PBL during the first 12 h, then all of the plumes moved upward reaching heights up to 3000 m. Moreover, the trajectories indicate that the air parcels traveled from northwest toward north and northeast direction which coincides with MODIS smoke plume paths (Fig. 13a and b). Therefore, the HYSPLIT forward trajectory analysis provides evidence that some cities in Alberta could be

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affected by the fires emissions after a short time (24–48 h) depending on the starting plume height.

A CO total column and surface composites for 10–20 July are displayed in Fig. 13c and d. The plume of CO expanded across the northeast of Alberta where the CO total column and surface exceeded 3.25×10^{18} molecules cm^{-2} and 300 ppb, respectively. Despite the limited vertical resolution of MOPITT measurements, a general enhancement of CO can be clearly seen for surface measurements where the CO mixing ratio close to fires was as high as 300 ppbv, in comparison with a CO mixing ratio of 60–90 ppbv in the background. However, the spatial pattern of total column and surface CO are not similar where the former is more distinct in the west area of Alberta where fires originated than the latter. The location of maximum surface CO is slightly shifted to eastward from that of maximum fire counts. This is likely due to the transport of CO with the prevailing westerly winds.

Although most of the fires are originated in northwest area of Alberta (for summer 2012), MOPITT images revealed the intense CO plumes in the east which match remarkably well with MODIS and HYSPLIT trajectories. This implies the substantial influence of long range transport on CO levels where its long lifetime allows plumes with elevated CO to travel long distances affecting air quality downstream of the point source emissions. Zhao et al. (2007) indicated that a high CO episode at a remote area can result from long-range transport from active biomass burning and biofuel burning areas rather than local air pollution.

Daily time series of in situ measurements at Athabasca Valley station for July 2012 reveals (Fig. 14b) elevated CO concentrations during the intense forest fire period. Although the total number of hotspots peaked on 10 July, the enhancement of CO was found to reach the maximum value later on 12 July where it exceeded 700 ppb. This further confirms the important effect of transport on atmospheric CO values.

Generally, the in situ measurements are in good agreement with MOPITT data, however the magnitude of in situ measurements is higher than surface MOPITT data. The reason could be due to the larger spatial footprint of MOPITT data (22 km × 22 km) while

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in situ measurements represent point data. In addition, since MOPITT is not very sensitive to the CO in the boundary layer, it is possible that the sharp surface features are masked and hence the retrieved CO values in the boundary layer are lower than reality during biomass burning emissions.

4 Summary and conclusions

This study demonstrated the potential use of MOPITT CO measurements to better understand and quantify the CO sources over Alberta. MOPITT-based climatology and inter-annual variations were conducted for 12 years (2002–2013) on spatial and temporal scales. MOPITT V5 multispectral product that uses both near-infrared and the thermal-infrared radiances for the CO retrieval were used. Available MOZAIC/IAGOS aircraft CO profiles over Calgary were used to validate MOPITT CO data. Additionally, CO ground measurements were compared to satellite data. The MODIS thermal anomaly product from 2001 to 2013 was employed to investigate the effect of seasonal variations of fires on climatological and inter-annual CO levels. To further recognize the fate and the impact of biomass burning emissions on air quality, forest fires on a sever day have been analyzed as a case study.

Seasonal climatological maps for CO total columns indicated conspicuous spatial variations in all seasons except in winter where the CO spatial variations are less prominent. High CO loadings are observed to extend from the North eastern to North western of Alberta, with highest values ($2.5–2.75 \times 10^{18}$ molecules cm^{-2}) in spring. The CO mixing ratios at the surface level in winter and spring seasons exhibited dissimilar spatial distribution pattern where the enhancements are detected in south eastern Alberta (east of Edmonton city) rather than north, with mixing ratio range of 250–300 ppb. Analyzing spatial distributions of omega at the 850 mb pressure level for four seasons implied that, conditions in northeast Alberta are more favorable for up lofting while in the south subsidence of CO emissions are more likely. Thus, meteorological parameters may affect the CO spatial distribution profile where the CO total columns show

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remarkable enhancements in the north while the surface CO experiences high values in the south area.

The time-altitudes climatology of the CO profiles as well as the inter-annual variability are investigated for Fort McMurray, Edmonton and Calgary regions to compare impact of various sources on CO loading. Monthly variations over Edmonton region are consistent with the general seasonal cycle of CO in Northern Hemisphere (Edwards et al., 2004) which exhibits significant enhancement in winter and spring, and minimum mixing ratios in summer. The typical seasonal CO variations over Fort McMurray area are less prominent, where there is an obvious rise of CO in summer. The same seasonal patterns are detected at various surface monitoring stations; however the magnitudes of in situ measurements are higher. Inter-annual variations of satellite data display a slightly decreasing trend for both regions while the decline trend is more evident from ground observations, especially in the Edmonton and Calgary regions. These discrepancies (between satellite and ground data) may be explained by larger MOPITT spatial resolution and its lower sensitivity to the surface CO.

MOPITT CO profiles are validated by comparing them to the available MOZAIC/IAGOS aircraft profiles after applying averaging kernel (Emmons et al., 2009). Both vertical distributions showed good agreement within the standard deviation at all pressure levels.

Time altitude CO profile measurements over the Edmonton and Calgary regions exhibited relatively elevated CO values in the lower troposphere than the corresponding values over the Fort McMurray area. However, the total column CO values are similar. This striking feature suggests that Edmonton and Calgary regions may be blanketed by regional pollution while the Fort McMurray area (northern Alberta) may be influenced by CO plumes transported either vertically or horizontally which could be from industry and/or the biomass burning. Temporal analysis of fire frequency showed that, the main biomass burning season is from May to July where the largest fires are clustered spatially in northern and central Alberta. The spatial distributions of fires match remarkably the spatial distributions of MOPITT CO total column in spring and summer. Addition-

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ally, there is a consistency between the time evolutions of high CO episodes that are monitored by satellite and ground measurements in the Fort McMurray area and the fire frequency peak time. This finding implies that biomass burning and its transport have interesting consequences for the tropospheric CO distribution in northern Alberta, given the complex meteorology that prevails in this area.

Since 2012 depicted high fire frequency, 10 July 2012 was selected to analyze the biomass burning smoke plumes. Daily time series of ground measurements in Fort McMurray revealed elevated CO concentrations on 12 July (> 700 pbb) which is two days after peak fire frequency (10 July). Furthermore MOPITT composite image for the fire severity period (10–20 July) displayed more intense CO plume in the east rather than west area where most of the fires originated. This result reflects the significant influence of long range transport of biomass burning emissions on CO levels which is further confirmed by MODIS smoke plume images and HYSPLIT forward trajectories.

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Table 1. The boundaries of study areas.

Name of study area	Latitude range	Longitude range
Fort McMurray	56.0 to 58.0° N	112.0 to 110.0° W
Edmonton	52.0 to 54.0° N	114.0 to 112.0° W
Calgary	50.0 to 52.0° N	115.0 to 113.0° W

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Table 2. Location, elevation and starting date of selected CASA monitoring stations.

Name of the station	longitude	latitude	elevation	Starting date
Calgary Central 2	51.0470	−114.0747	1051.0	01 Apr 2008
Calgary Central	51.0471	−114.07315	1051.0	01 May 1979
Calgary East	51.0094	−114.0253	1028.0	01 Aug 1974
Calgary Northwest	51.0792	−114.1419	1106.0	01 Aug 1974
Fort McMurray-Athabasca Valley	56.7328	−111.3903	260.0	01 Dec 1997
Edmonton Central	53.5444	−113.4988	663.0	03 Dec 1976
Edmonton East	53.5481	−113.3682	679.0	01 Oct 1972
Edmonton Northwest	53.5942	−113.5400	679.0	12 Jul 1973
Edmonton South	53.5001	−113.5261	681.0	21 Sep 2005

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Figure 1. Alberta's oil sands deposits in the Athabasca, Peace River and Cold Lake regions (Percy, 2013).

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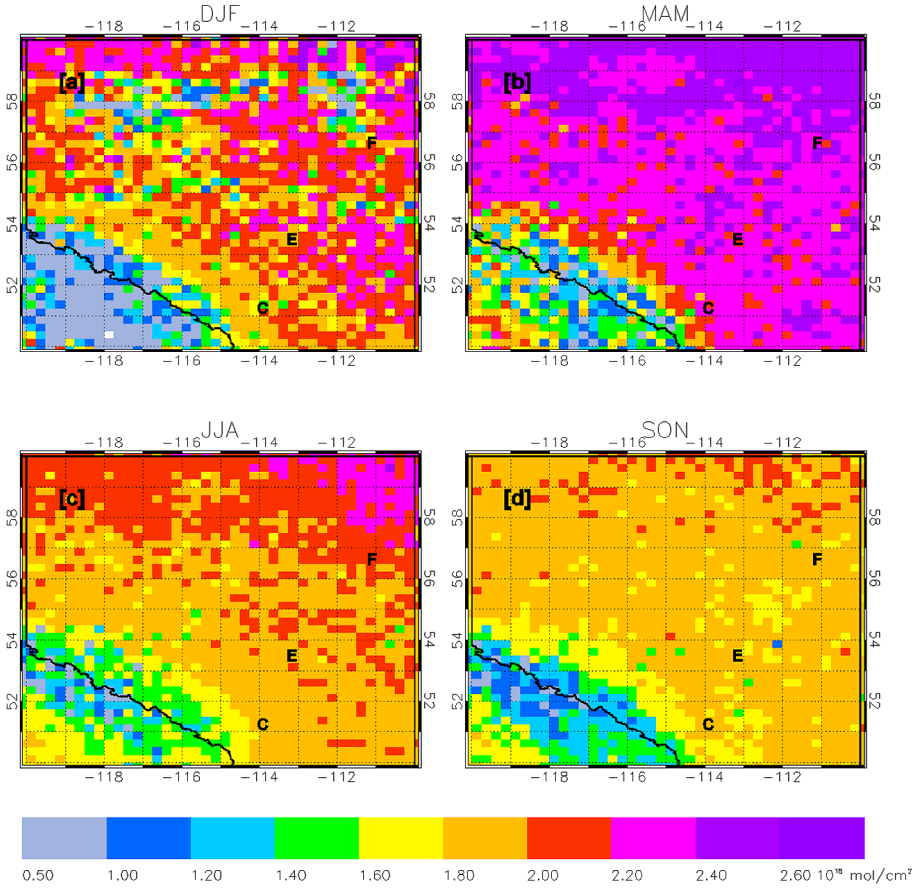

Figure 2. The MOPITT daytime CO total column measurements over Alberta for the period March 2002 to December 2013 in **(a)** winter, **(b)** spring, **(c)** summer and **(d)** fall. The symbol F, E and C represent Fort McMurray, Edmonton and Calgary cities, respectively. Data are gridded at 0.25° × 0.25° resolution.

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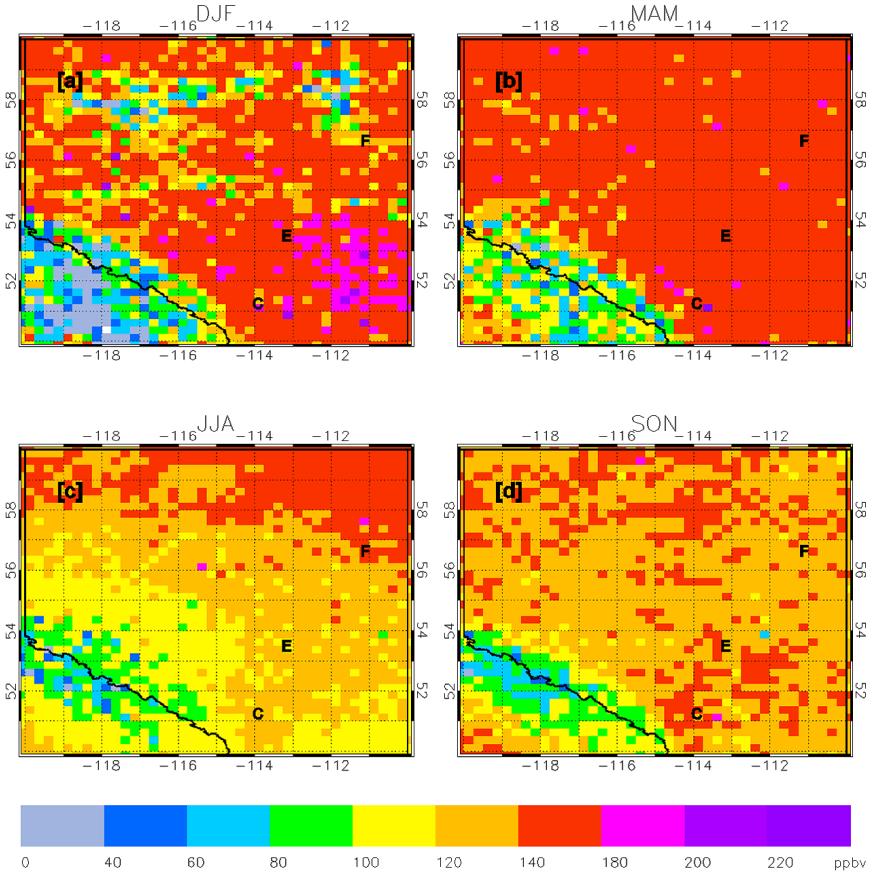

Figure 3. MOPITT daytime CO mixing ratios at the surface level over Alberta for the period March 2002 to December 2013 in **(a)** winter, **(b)** spring, **(c)** summer and **(d)** fall. The symbol F, E and C represent Fort McMurray, Edmonton and Calgary cities, respectively. Data are gridded at 0.25° × 0.25° resolution.

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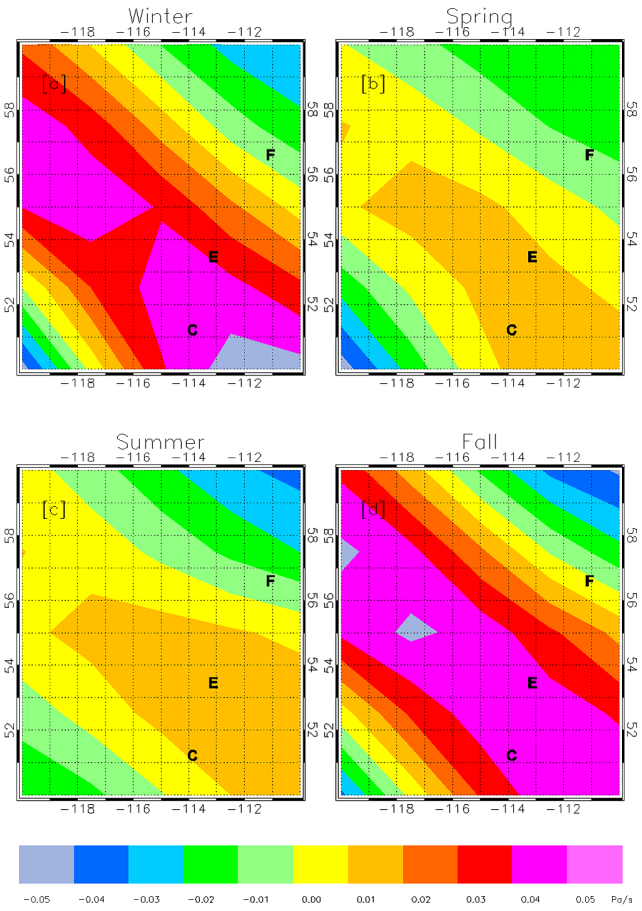

Figure 4. Spatial distributions of Omega at pressure level 850 mb for the period from 2002 to 2013 in winter **(a)**, spring **(b)**, summer **(c)**, fall **(d)**.

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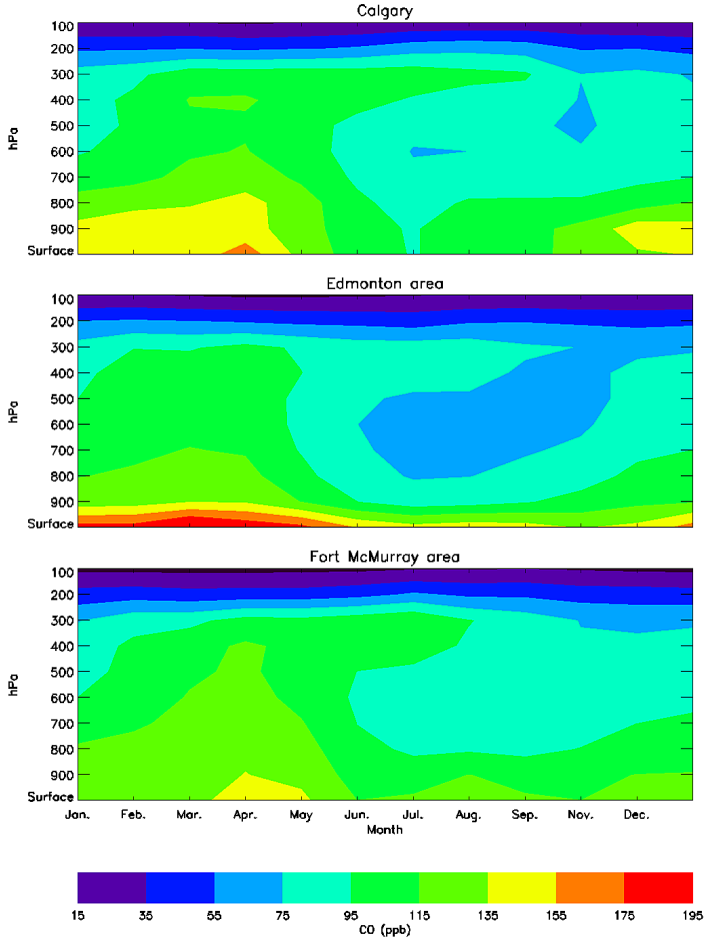

Figure 5. Climatological MOPITT CO profiles for the period March 2002 to December 2013 over Calgary, Edmonton, and Fort McMurray area.

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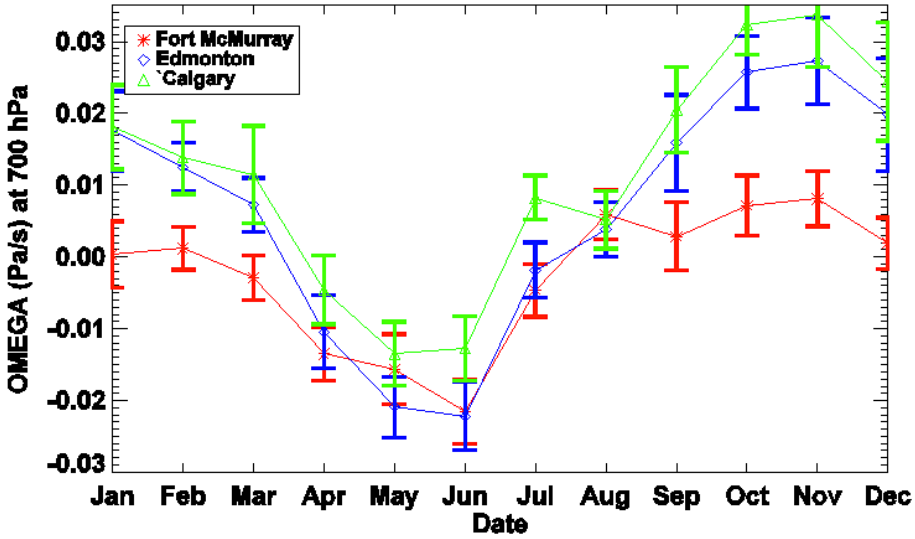

Figure 6. Omega averages at 700 hPa from 2002 to 2013.

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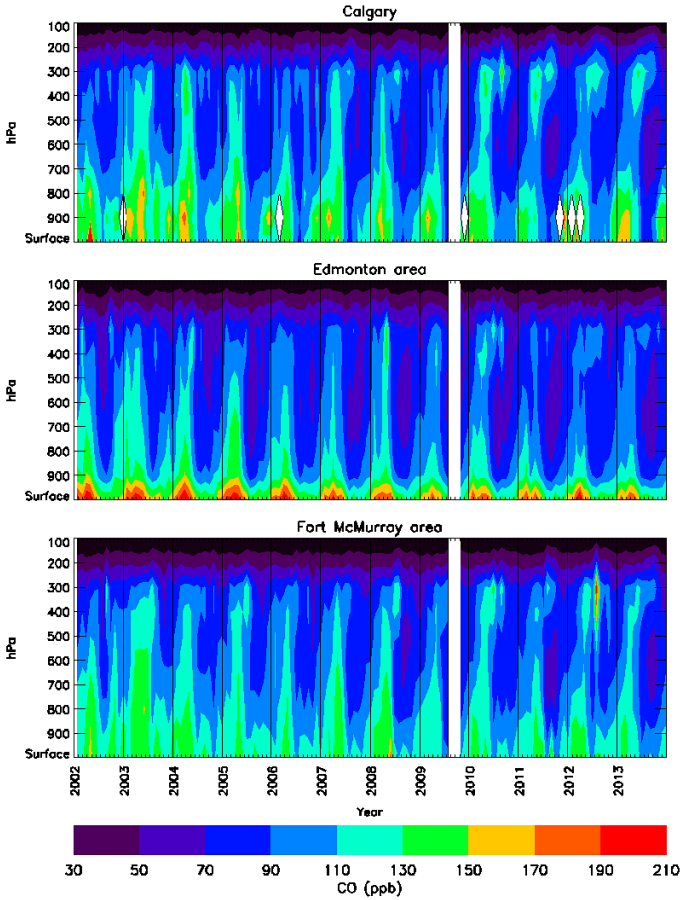

Figure 7. The 12 year inter-annual variation monthly averaged daytime MOPITT CO mixing ratios (ppb) as measured by MOPITT since January 2002 to December 2013 over Calgary, Edmonton, and Fort McMurray areas.

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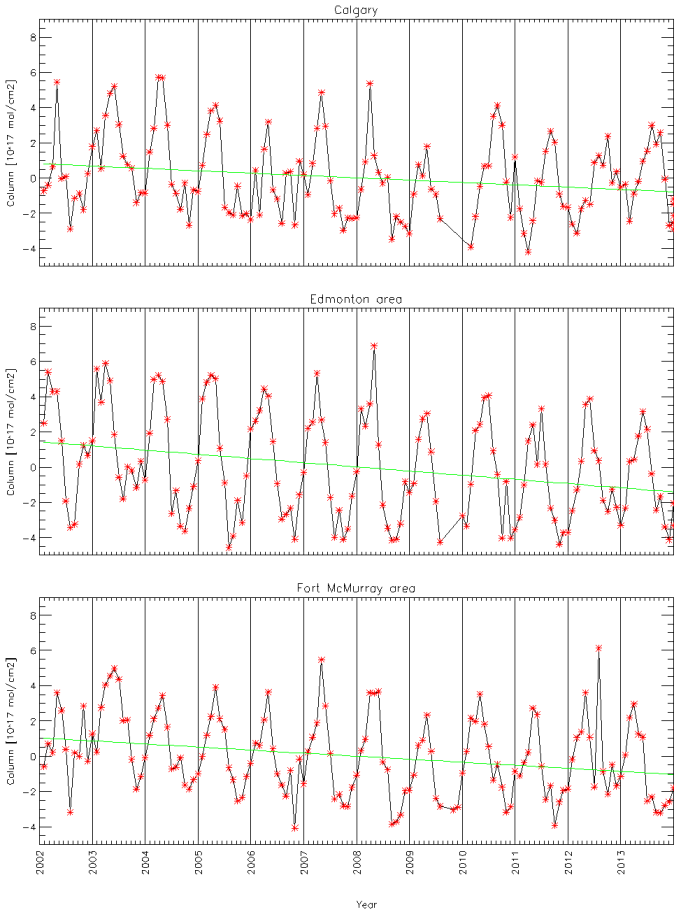

Figure 8. The 12 year inter-annual variations monthly averaged daytime MOPITT CO total column measurements for the period January 2002 to December 2013 over Calgary, Edmonton, and Fort McMurray areas.

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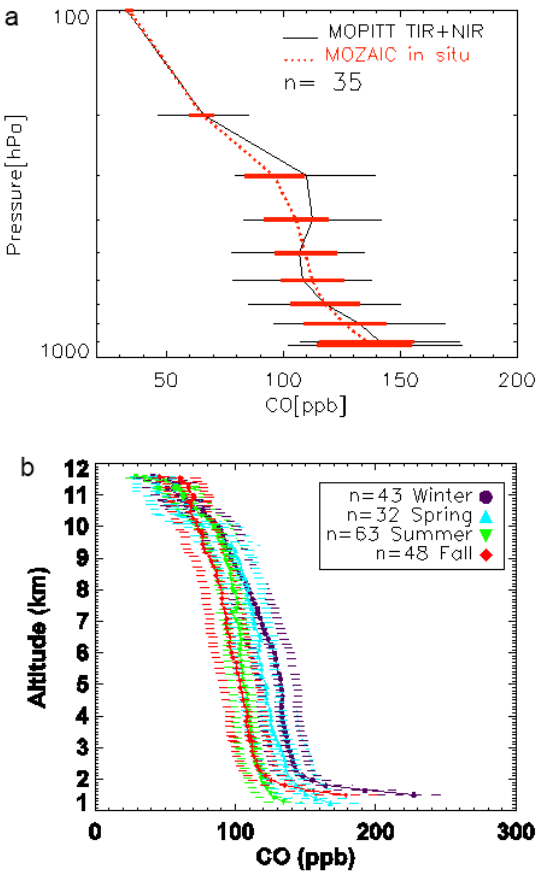

Figure 9. MOZAIC/IAGOS (AK) and the corresponding MOPITT CO profiles **(a)** and MOZAIC/IAGOS seasonal averages CO profiles **(b)**. The horizontal bars are standard errors.

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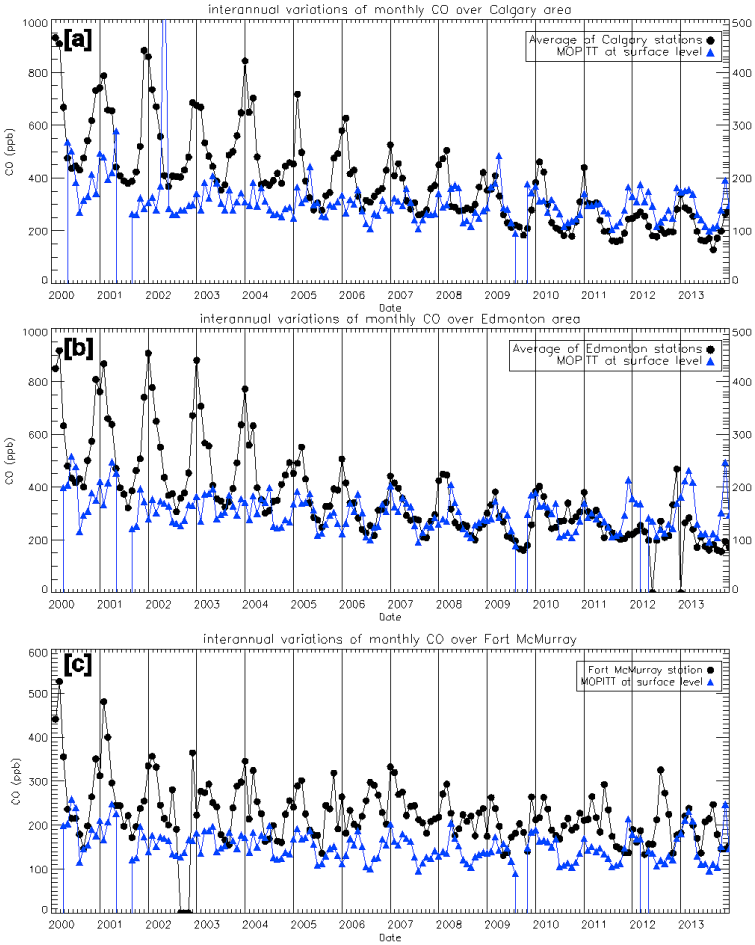

Figure 10. CASA CO in situ measurements (left axis) and MOPITT CO at surface level (right axis) at **(a)** Calgary, **(b)** Edmonton and **(c)** Athabasca Valley.

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Satellite remote sensing of tropospheric CO over Alberta using MOPITT data

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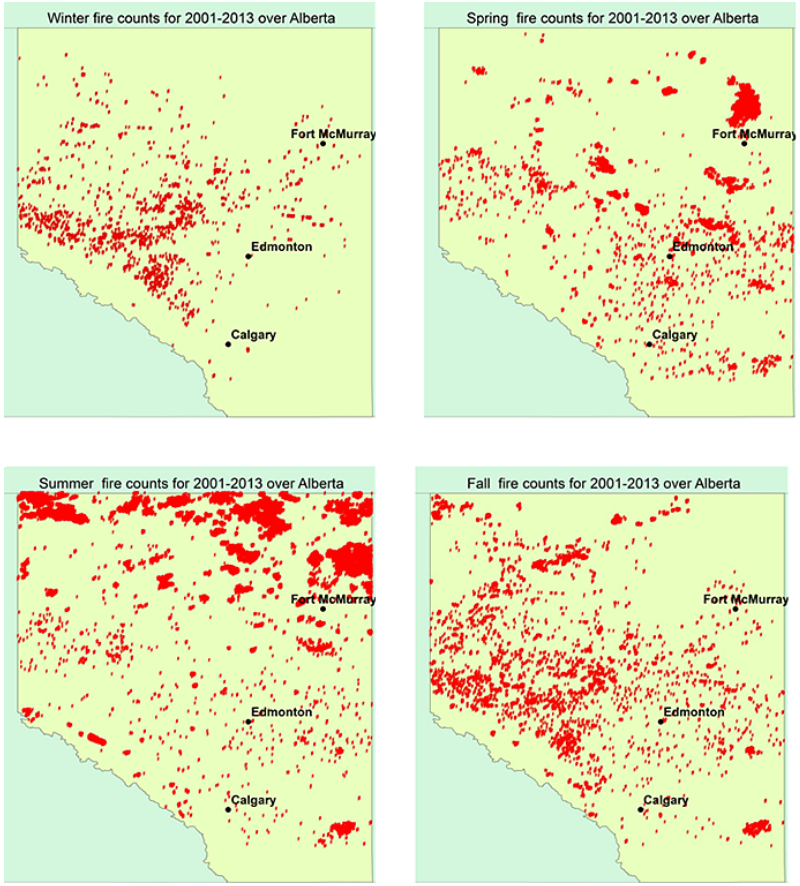

Figure 11. Seasonal variations of MODIS fire counts for the study period (2001–2013) over Alberta.

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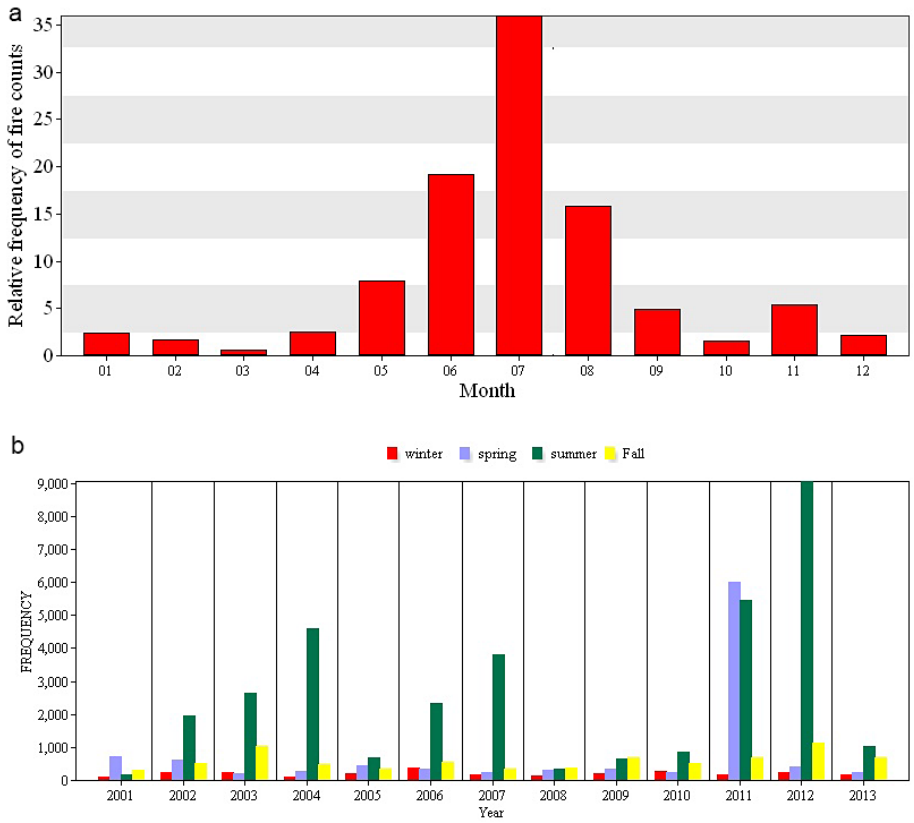

Figure 12. (a) Monthly variations of MODIS fire counts for the study period (2001–2013) over Alberta, **(b)** inter-annual variations of seasonal fire frequency.

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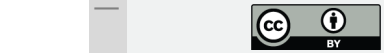

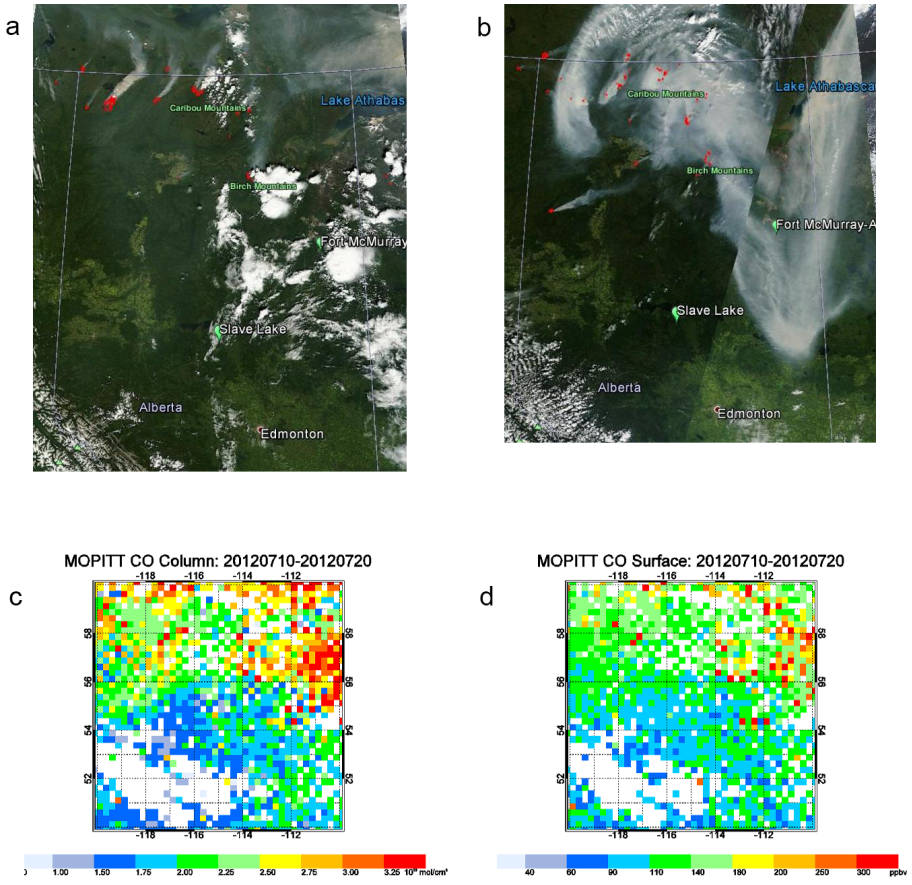

Figure 13. MODIS true image combined with fire points (red) **(a)** on 10 July 2012 and **(b)** on 11 July 2012, **(c)** MOPITT CO total column from 10–20 July 2012 over Alberta, **(d)** MOPITT surface CO from 10–20 July 2012 over Alberta.

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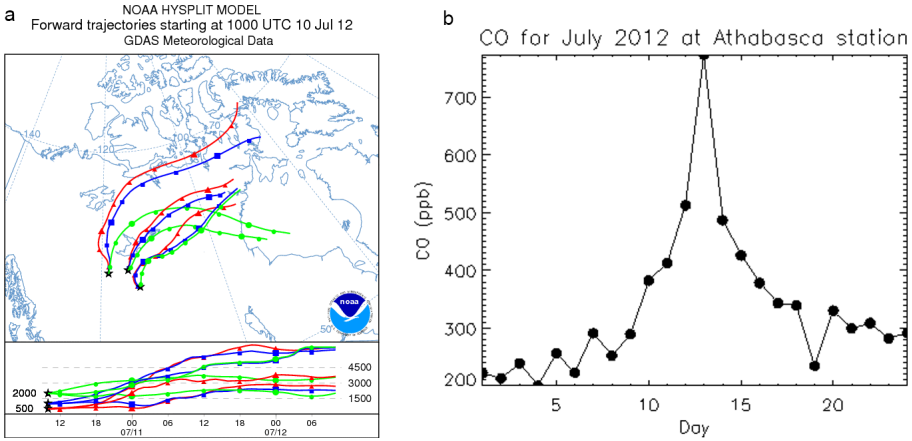

Figure 14. (a) 48 HYSPLIT forward trajectory started on 10 July 2012, and **(b)** daily CO at Athabasca Valley station for July 2012.

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