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Impact of wildfires on some greenhouse gases over continental USA: A study based on satellite data

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ABSTRACT

Wildfire episodes are becoming more rampant with global warming and climate change. Every year it causes lot of damage in terms of burnt acres and also impacts the air quality and climate through emission of various trace greenhouse gases. As emissions from large fires increase with time, it is essential to monitor the extent and spatial distribution of such changes that can have both short term and long-term implications in terms of human health and feedback on global radiative forcing. In this paper we have used the vertical profile distributions of some of the key trace gases, from AQUA-AIRS sensor to better understand the impact of wildfires in terms of magnitude, spatial and seasonal distribution. Our study shows the impact of season on fire emission in the planetary boundary layer and the free troposphere and also highlights areas in the continental United States (CONUS) where different trace gas emissions are more preponderant. Overall it successfully demonstrates the applicability of satellite-based sensors for regular monitoring of fire related trace gas emissions.

1. Introduction

Wildfires are a recurring problem, not only for (CONUS) but also over most parts of the globe. It's becoming more rampant and damaging with climate change and increasing spring and summer time temperatures (Piñol et al., 1998; Westerling, 2006; Westerling and Bryant, 2007; Marlon et al., 2008). In 2015 itself CONUS has had one of the largest wildfire in recorded history, in terms of acres damaged. A total of 10,125,149 acres were damaged by fire in 2015 (*ref*: *NIFC fire statistics in* Section 2.1.2), making it the 4th worst fire in recorded history and the largest in the last decade. The total acres burnt were almost 35% higher than the ten-year average, which is 6,464,947 acres. However a bulk of those fire acres was caused by an unprecedented amount of fire acreage in Alaska alone, (5,110,942 acres) which accounted for more than 50% of the nation's acreage consumed in 2015.

Apart from acres of damaged land and loss of property, wildfires have a serious impact on environment and air quality. Burning forests release nitrogen oxides (NOx) and volatile organic compounds (VOCs) in the atmosphere (Andreae and Merlet, 2001; Christian et al., 2009; Yokelson et al., 2007), which then gets converted to Ozone (O_3) leading to increased tropospheric O_3 (Fishman et al., 1997; Thompson et al., 2001; Liu et al., 2002). Wildfires also releases several other greenhouse gases (GHG) like water vapor, Methane (CH_4), Carbon Dioxide (CO_2), depending on the moisture content, composition and structure of fuels and the extent of combustion of the fuels (Ward and Hardy, 1991; Langmann et al., 2009; Larkin et al., 2009). Other than these GHGs wildfires are also known to cause emission of Carbon Monoxide (CO), different aerosol and particulate matters like PM_{10} and $PM_{2.5}$, which can quickly spread and diffuse to other areas, depending on the plume height, injection rate, weather and residence times.

Such emission of GHGs and aerosol particulate matters poses serious health risk (*ref*: OEHHA, 2008). This can be more pronounced for GHGs and trace gases that have longer residence times in the troposphere like CH_4 and CO (Junge, 1974). These GHGs can also impact the climate system through radiative forcing (Bowman et al., 2009; Bond et al., 2013). Aerosols from wildfires can impact the cloud formation both positively

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and negatively through formation of more cloud condensation nuclei and absorbing, respectively. Increased emission of water vapor and other GHGs can impact surface albedo and radiative forcing and in turn to lead to warmer climate, thus producing a positive feedback cycle.

The number of wildfires, and acres of land, damaged from wildfires, have shown an increasing trend in recent years, and are projected to increase further, because of climate change (Groot et al., 2013; Groot and Flannigan, 2014). Hence it's imperative to get a precise sense of the extent of impact these GHG emissions poses from wildfires. There have been a lot of studies where satellite data has been used to estimate the burned area or amount of biomass burning and plant productivity and relate that to emission factors and emission fluxes for different trace gases and particulate matter (Werf et al., 2010; Akagi et al., 2010; Schreier et al., 2015). Our study is the first of its kind to leverage satellite data to map the spatial distribution of GHGs caused by large fires. In this paper we have used satellite data to summarize the extent and distribution of key GHG components like tropospheric O_3, CH_4 and water vapor (H_2O). We have also highlighted the impact of wildfires on CO, which though not a GHG, is still a serious threat to human health. The focus of this paper is to highlight their distribution specifically as linked with the extent and spread of wildfires.

2. Data and methodology

2.1. Data used for this study

2.1.1. Image data

We have primarily used the vertical distribution of $O_{3,}$ CO and CH_4, at different pressure levels, derived from the Atmospheric Infrared Sounder (AIRS) instrument suite. The AIRS instrument suite, launched on May 2002 onboard NASA's Aqua platform, comprises the AIRS instrument per se along with a multi-channel Atmospheric Microwave Sounder (AMSU) and the Humidity Sounder Brazil (HSB) instrument. The AIRS instrument itself is a hyper-spectral sensor consisting of 2378 spectral channels in the infrared (IR) range between from 3.7 μm to 15.4 μm, and 4 visible/near-infrared channels. Prominent absorption features of O_3 (9.6 μm), CO (4.6 μm) and CH_4 (7.6 μm) in the AIRS IR spectrum is used to derive vertical profiles of these trace gases at different pressure levels, along with profiles of H2O and Carbon Dioxide (CO_2).

In this study we have used the AIRS standard Level 3 (L3) daily product (AIRX3STD), which averages daily Level 2 swath based observations whose quality indicators mark them as "best" or "good". It contains information for a temporal period of 24 h for both the ascending (daytime) and descending (night) orbits, of which only the ascending (daytime) observations have been used in this study. This data is available at a spatial resolution $1° \times 1°$ grid cells. This data has been obtained from the NASA Goddard Data and Information Services Center (GES DISC) for all days from 2003 to 2015.

2.1.2. Fire statistics

We have used the monthly statistics of acres burned by wild fires, from 2003 to 2015, for all of CONUS, available from NOAA National Centers for Environmental Information (https://www.ncdc.noaa.gov/societal-impacts/wildfires/month/0?params[]=acres&params[]=fires). National Interagency Fire Center (NIFC) compiles the wildfire statistics through 10 regional Geographic Area Coordination Centers (GACC), covering the entire CONUS. These wildfire frequency and burn statistics are aggregated from reports of large wildfire incidents (100+ acres of timber and 300+ acres of grasslands) through "Incident Status Summary" reports.

2.1.3. Atmospheric data

Pressure level climate datasets for geopotential height and vertical velocity (omega) have been derived from the NCEP/NCAR Reanalysis 1 project (Kalnay et al., 1996) dataset, from NOAA Earth System Research Laboratory (ESRL), Physical Sciences Division (PSD). These data are at $2.5° \times 2.5°$ spatial grid and at 17 pressure levels.

2.1.4. Atmospheric composition data

Model atmospheric daily CH4 concentration (mole fraction in ppb) and monthly CH4 surface flux data have been obtained from the Monitoring Atmospheric Composition and Climate (MACC) dataset. MACC is part of the European system for monitoring the Earth called Copernicus, that employs a comprehensive system of earth observation satellites, in-situ observations and models to monitor key parameters over land, ocean and atmosphere, supporting a number of applications, across diverse areas. MACC is part of the Copernicus atmospheric service and provides data records on global atmospheric composition and air quality over Europe.

The MACC CH4 surface flux and concentration comes from a flux inversion reanalysis system based on the TM5-4DVAR inverse modeling system (Bergamaschi et al., 2009; Bergamaschi et al., 2013; Meirink et al., 2008). The data used in this paper, assimilated measurements from NOAA global cooperative air sampling network in the inversion framework. The MACC data is available at a spatial resolution of $4° \times 6°$ in vertical and horizontal grid spacing respectively. The daily concentration in molar fraction, is available in 25 hybrid pressure levels.

2.2. Method

For the purpose of this study we focused on CONUS and looked at the distribution of O_3, CH_4, CO and H_2O, mainly at the lower troposphere region. In this study we have looked at the AIRS daily data for the ascending orbit (daytime) only. All missing values in the daily data are first filled in through a piecewise local interpolation step, applied in the temporal domain. Seasonality is removed from the daily data by subtracting the long-term daily means and the daily anomalies are weighted by the cosine of latitude to offset any artifacts produced due to gridding, at high latitudes.

The purpose of this study is to highlight the impact of wildfires on GHG emissions over the CONUS. To emphasize these short-term fluctuations we applied a 2–15 day Lanczos band-pass filter to the anomaly time series with sufficient weights to get a precise filter response. Band-pass filtering ensures that all frequencies or wavenumbers above or below the desired window are removed and serves to highlight frequency ranges that are of interest. To account for the Lanczos filter weights our effective study period is reduced to 2004–2014, ignoring a year's worth of daily data on either side of the time series. In order to minimize any bias arising from different scales of the different variables, we have standardized the anomalies by dividing by their standard deviations. This has been done to minimize bias for subsequent analysis that combines different state variables. Finally for ease of analysis and comparison, we have aggregated all daily data to monthly values by selecting the daily maxima as the compositing criteria. The maximum value criterion was chosen so as to enhance any effect of fire and not lose it by way of averaging.

We combined three of the monthly observations for O_3, CH_4, CO to compute multivariate Empirical Orthogonal Function (EOF) patterns. Multivariate EOF has been shown to be very effective in maximizing covariance not only across temporal and spatial domains but also across the state variables (Navarra and Simoncini, 2010; Sparnocchia et al., 2003; Hermann et al., 2013). It is an extension of the simple EOF analysis whereby more than one state variable are combined in a single data field, making sure that they all have same temporal extension (1).

$$X = \begin{bmatrix} a_1 \dots & a_n \\ b_1 \dots & b_n \end{bmatrix} \quad (1)$$

where $a_1 \dots a_n$ represents one time series $\boldsymbol{A}$ and $b_1 \dots b_n$ represents