Quantitative Characterization of Emissions from Biomass Burning using Remote Sensing Measurements

Clare Paton-Walsh[a, *], Emma Young[a] and David Griffith[a]

[a]University of Wollongong, New South Wales, Australia, (clarem@uow.edu.au).

Abstract:
We present a new method for deriving total emissions estimates from large vegetation fires using satellite-based measurements of aerosol optical depth. This method is based upon simultaneous measurements of total column amounts of trace gases and aerosol optical depth of the atmosphere through smoke plumes from Australian fires. These measurements were derived from ground-based solar remote sensing spectrometers in the infrared and UV-visible spectral regions and also provide emission ratios that may be used in more conventional bottom-up estimates of total emissions.
Measurements of emissions from Australian forest fires are relatively sparse given the significance of this source to the global emissions budget from biomass burning. Additional measurements of emission ratios of a number of trace gases have been made using open-path FTIR measurements through smoke plumes from hazard reduction burns in New South Wales.

1. INTRODUCTION

Large vegetation fires like the Black Saturday bushfires are a significant source of both atmospheric trace gases and of aerosols. Fires are also highly variable in their extent and intensity and so biomass burning is a major contributor to the annual variability of tropospheric composition. For this reason global chemical transport models require estimates of the total emissions of both gases and aerosols into the atmosphere that result from such fires.

Total emissions of a particular gas from fires are normally calculated as the product of the area burned, the average fuel load, the efficiency of combustion, and the emission factor for the gas of interest. In recent years inventories that estimate fire emissions on a global scale for a number of years have been developed eg [*Kasischke et al.*, 2004; *van der Werf et al.*, 2006]. These inventories use satellite imagery to estimate burned area and biogeochemical models in conjunction with satellite data to estimate fuel loads, whilst combustion efficiency and emission factors are based on field measurements available in the literature. Such methods are known as "bottom up" estimates because emissions are multiplied up from an estimated amount of fuel consumed on the ground.

An alternative approach, described as a "top down" estimate uses satellite measurements of a biomass burning product such as carbon monoxide, combined with inverse modelling to infer the source strength of emissions [*Arellano et al.*, 2006; *Pfister et al.*, 2005]. Another interesting approach has been to use satellite measurements of fire radiative energy as a basis for estimating total emissions [*Wooster*, 2002].

Unfortunately the uncertainties involved in estimating total emissions from fires are large. An additional concern is that top-down and bottom-up estimates have sometimes shown poor agreement [*Arellano et al.*, 2006; *Hoelzemann et al.*, 2004]. For this reason alternative techniques that have different uncertainties are useful additional tools for making estimates of the emissions to the atmosphere that result from vegetation fires.

In this paper we describe a top-down method using satellite measurements of aerosol optical depth. In addition some measurements of trace gases emission ratios (for use in tradional methods of estimating fire emissions) made at hazard reduction burns in New South Wales, Australia are also described.

2. A TOP-DOWN METHOD USING SATELLITE MEASUREMENTS OF AEROSOL OPTICAL DEPTH

The top-down method used in this study utilises the strong correlations between aerosol optical depth (AOD) at around 500nm and column amounts of many trace gases in smoke plumes aged a few hours to a day or two, (see figure 1) [*Paton-Walsh et al.*, 2004]. MODIS instruments onboard NASA's Aqua and Terra satellites are used to measure AOD at 550nm and values are averaged over 1° by 1° grid boxes [insert MODIS references]. All grid boxes in the region of the active fires with AOD values above a threshold value of 0.2 are included in the calculation and assumed to result from smoke from the fires. A normal background AOD amount of 0.1 is subtracted from each of the indentified 1° by 1° grid boxes to yield the excess AOD produced by the fires.
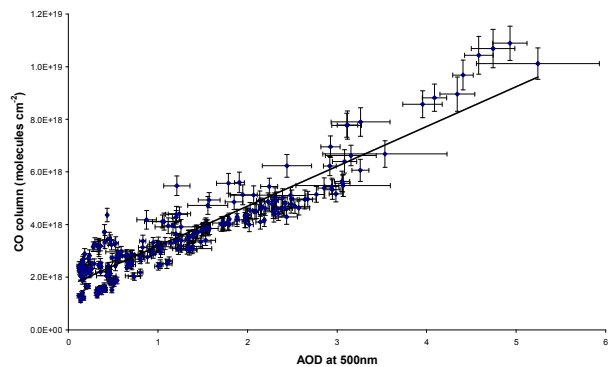

Figure 1: the strong correlation between aerosol optical depth (AOD) at around 500nm and column amounts of carbon monoxide, $R^2 = 0.89$.

The excess AOD values are then translated into equivalent excess amounts of trace gases in the smoke plumes. The corresponding total column amounts of carbon monoxide, hydrogen cyanide, formaldehyde, ammonia, acetylene, ethylene, ethane, formic acid and methanol in the region are determined by the relationships established between column amounts of these gases and AOD by coincident and co-located measurements through smoke plumes from south east Australian vegetation fires from remote sensing instrumentation at Wollongong (34 S, 151 E) [*Paton-Walsh et al.*, 2005; *Paton-Walsh et al.*, 2008]. Total column amounts are then translated into total mass of the emitted gas by multiplying by the area and the molecular weight and dividing by Avogadro's number.

The conversion for carbon monoxide (CO) is given by **Error! Reference source not found.** below:

$$M_{CO} = \frac{AOD_{excess}.G_{CO:AOD}.A_{grid}}{N_A}.MW_{CO}$$

(1)

Where

- M_{CO} = enhanced mass of CO in the region as a result of the fires
- AOD_{excess} is 0.1 less than the 1° by 1° grid averaged MODIS AOD in each grid box that had a value above 0.2
- $G_{CO:AOD}$ is 1.5 x10^{18} molecules cm^{-2} (the gradient of column CO to AOD determined in Paton-Walsh *et al* [2005])
- A_{grid} is 1.02 x10^{14}- the area of the grid boxes in cm^2 using conversion factors of 111.12 km for 1° latitude and 92.12 km for 1° longitude
- N_A is Avogadro's Number = 6.02 x10^{23} mol^{-1} and
- MW_{CO} is the molecular weight of CO (28 g mol^{-1})

Summing the mass of enhanced CO in all of the contributing grid boxes gives the total enhanced atmospheric mass of CO in the area on each day.

Figure 2 shows the 1° by 1° grid averaged AOD measured by MODIS instruments on the 7th February 2009 (Black Saturday). The white pixels represent areas where the data has been rejected by the MODIS algorithm due to cloud interference, sea glint or other reason. Calculations for these two days yield estimates for the emitted mass of CO of 0.46 Tg on the 7th February and 0.46 Tg on the 8th February. Clearly there is a problem caused by parts of the plume being missed in the white pixels. Also it is not obvious how much of the enhancements seen on the 8th February and subsequent days result from emissions on the 7th February that have not been dispersed from the region.
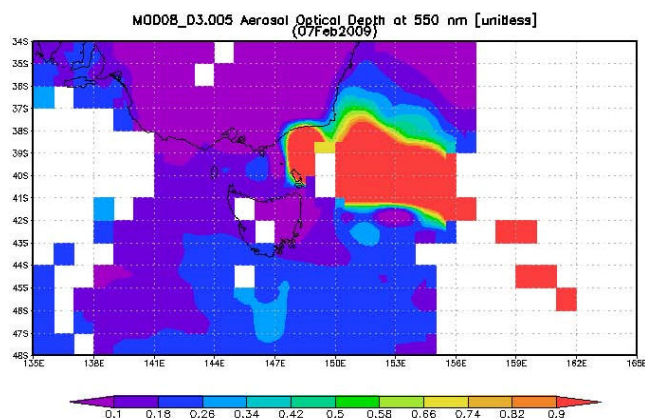

Figure 2: 1° by 1° grid averaged AOD measured by MODIS instruments on the 7th February 2009 (Black Saturday).

The chemical transport model MOZART [*Emmons et al.*, 2009] is used to model the dispersion of the plumes and thereby estimate the effects of double-counting and of missing data. For each day of the fires a mass of CO emissions defined by the excess AOD detected is released into the model from locations proportional to the mean fire radiative power measured in the region for February 2009. The CO is tagged separately for each day and treated like a tracer (with no chemistry) but with an atmospheric lifetime of 3.8 days to mimic AOD [*Edwards et al.*, 2006]. The model outputs separate concentration fields for each days emissions and so the double-counting is estimated by summing all previous emissions still remaining and multiply by the fraction of 1° by 1° grid boxes with real AOD data. (This is to account for the amount of previous emissions also missed in the white pixels).

The model output can also be used to estimate the likely magnitude of the underestimate caused by the missing data.

A more detailed description of this method may be found in *Paton-Walsh et al,* [2010].

3. MEASUREMENTS OF TRACE GASES EMITTTED FROM HAZARD REDUCTION BURNS IN NEW SOUTH WALES FORESTS

A low resolution Bomem MB-100 Series FTIR spectrometer, fitted with a Meade 12" LX200 telescope, was used to record infrared spectra at two hazard reduction burns. The spectrometer was equipped with a built-in infrared source and a Graseby Infrared liquid nitrogen cooled Mercury Cadmium Telluride (MCT) detector. The spectrometer was mounted on a tripod approximately 1m above the ground and aligned with a retroreflector positioned in the field. Single beam spectra were recorded every 30 seconds (6 co-added scans per spectrum) before, during and after each burn at the maximum 1 cm^{-1} resolution.

Max Allen Drive hazard reduction burn measurements

Figure 3: the retro reflectors are just visible up the slope at Max Allen Drive hazard reduction burn.

The Max Allen Drive hazard reduction burn was a burn to reduce surface fine fuels and some elevated fine fuels from an

estimated 18-26 tonnes per hectare to 5 tonnes per hectare over at least 75 percent of a 4.8 hectare (0.048 km^2) area within Lane Cove National Park (see Figure ? for the burn map). The burn took place within a single day, the 31st August 2010. The dominant fuel type was dry sclerophyll open woodland, which had not been burnt since the late 1970-80s. Drip torches were used to ignite the burn from the northern-most edge, followed by ignition of the north-western boundary with ignition ending in the relatively small section of vegetation between Depot Road and the Lane Cove National Parks and Wildlife Service (NPWS) depot. The spectrometer was situated within the NPWS depot and aligned with the retroreflector situated 50 ± 2 m away on the edge of Depot Road at an angle of elevation of approximately 15 degrees.

Gibberagong hazard reduction burn measurements

The Gibberagong hazard reduction burn was a burn conducted by the New South Wales National Parks and Wildlife Service (NSW NPWS) to reduce the extreme fuel hazard (20-25 tonnes per hectare) over a 148.5 hectare (1.485 km^2) area of the Ku-Ring-Gai Chase National Park (see Figure ? for a map of the area burned). The area had not burned within the last 20 years resulting in the growth of very dense Banksia/Hakea heath along the ridgelines and sclerophyll shrub forest, consisting mainly of bloodwoods and stringybarks, at lower elevations [*Clark*, 2010]. Ignition of the Gibberagong hazard reduction burn took place on a single day, the 28th September 2010, which is when all open-path FTIR measurements of smoke emissions were recorded.
The Bomem MB100 FTIR spectrometer, equipped with the telescope, was set up on the Murrua Trail (which was a control line during the burn) and aligned with the retroreflector positioned on the trail approximately 41 m away (see Figures ? and ? for the approximate positions and to view the setup). The total pathlength travelled by the infrared beam between the source and the detector was 84 ± 2 m.

Figure 4: the spectrometer's telescope is in the foreground to the right and the retro reflectors are just visible at the end of the line of traffic cones at the Gibberagong hazard reduction burn.

The setup for the Gibberagong hazard reduction burn differed from the Max Allen Drive hazard reduction burn in that there were no fires burning directly in the path of the infrared beam. Fires were burning to the north, north-west, west and south-west and smoke from these fires was transported through the measurement path due to the wind, which was predominantly north-westerly on the day. For a significant part of the measurement period, vegetation was burning directly alongside the Murrua Trail (see Figure ?b), supplying plenty of smoke to the measurement path. For the rest of the time the measurement path was filled to varying degrees with smoke, with the retroreflector completely obscured by smoke for intermittent and brief periods.

Emission ratios from Australian temperate forest fires

The recorded spectra were analysed to obtain trace gas concentrations across the measurement path length [*Griffith*, 1996]. Emission ratios have been calculated for C_2H_4, H_2CO and NH_3 with respect to both CO and CO_2, using the mixing ratios measured in smoke from both the Max Allen Drive and Gibberagong hazard reduction burns. This data will be presented at the conference with an example given below for acetylene with respect to carbon dioxide measured at the Gibberagong hazard reduction burn. The gradient of a generalised least squares regression to this data yields an emission ratio of 0.0009 ± 0.0002 from the 232 recorded spectra.
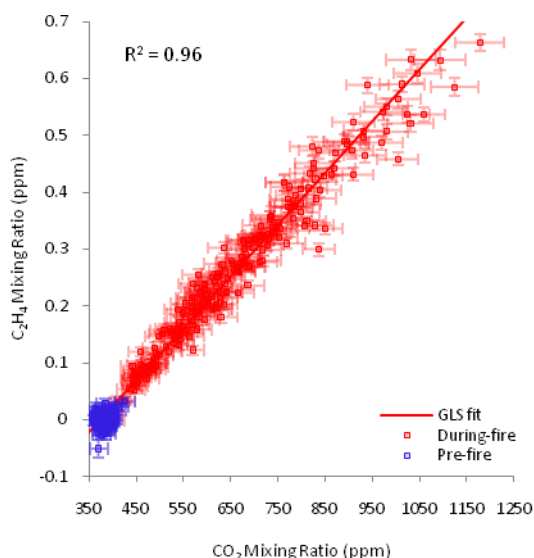

Figure 5: concentrations of acetylene are strongly correlated with carbon dioxide concentrations is the smoke plumes.

4. SUMMARY

A new method for deriving total emissions estimates from large vegetation fires using satellite-based measurements of aerosol optical depth has been described. This method is based upon simultaneous measurements of total column amounts of trace gases and aerosol optical depth of the atmosphere through smoke plumes from Australian fires. Additional measurements of emission ratios of a number of trace gases have been made using open-path FTIR measurements through smoke plumes from hazard reduction burns in New South Wales.

REFERENCES

Arellano, A. F., P. S. Kasibhatla, L. Giglio, et al. (2006), Time-dependent inversion estimates of global biomass-burning CO emissions using Measurement of Pollution in the Troposphere (MOPITT) measurements, *Journal of Geophysical Research-Atmospheres*, *111*(D9).

Clark, R. (2010), *National Parks & Wildlife Service Level 2 Prescribed Burn Plan (Gibberagong HR)*, NSW National Parks & Wildlife Service, Department of Environment Climate Change and Water.

Edwards, D. P., G. Petron, P. C. Novelli, et al. (2006), Southern Hemisphere carbon monoxide interannual variability observed by Terra/Measurement of Pollution in the Troposphere (MOPITT), *Journal Of Geophysical Research-Atmospheres*, *111*(D16), 9.

Emmons, L. K., S. Walters, P. G. Hess, et al. (2009), Description and evaluation of the Model for Ozone and Related chemical Tracers, version 4 (MOZART-4), *Geosci. Model Dev. Discuss.*, *2*(2), 1157-1213.

Griffith, D. W. T. (1996), Synthetic calibration and quantitative analysis of gas-phase FT-IR spectra, *Applied Spectroscopy*, *50*(1), 59-70.

Hoelzemann, J. J., M. G. Schultz, G. P. Brasseur, et al. (2004), Global Wildland Fire Emission Model (GWEM): Evaluating the use of global area burnt satellite data, *J. Geophys. Res.*, *109*(D14S04).

Paton-Walsh, C., N. Jones, S. Wilson, et al. (2004), Trace gas emissions from biomass burning inferred from aerosol optical depth, *Geophysical Research Letters*, *31*(5).

Paton-Walsh, C., N. B. Jones, S. R. Wilson, et al. (2005), Measurements of trace gas emissions from Australian forest fires and correlations with coincident measurements of aerosol optical depth, *Journal Of Geophysical Research-Atmospheres*, *110*(D24).

Paton-Walsh, C., S. R. Wilson, N. B. Jones, et al. (2008), Measurement of methanol emissions from Australian wildfires by ground-based solar Fourier transform spectroscopy, *Geophysical Research Letters*, *35*(8).

Paton-Walsh, C., L. K. Emmons, and S. R. Wilson (2010), Estimated Total Emissions of Trace Gases from the Canberra Wildfires of 2003: A new method using satellite measurements of aerosol optical depth & the MOZART chemical transport model, *Atmospheric Chemistry and Physics Discussions*.

Pfister, G., P. G. Hess, L. K. Emmons, et al. (2005), Quantifying CO emissions from the 2004 Alaskan wildfires using MOPITT CO data, *Geophysical Research Letters*, *32*(11).

Wooster, M. J. (2002), Small-scale experimental testing of fire radiative energy for quantifying mass combusted in natural vegetation fires, *Geophysical Research Letters*, *29*(2027).

ACKNOWLEDGEMENTS