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# Australia's Black Saturday fires - comparison of techniques for estimating emissions from vegetation fires

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## Abstract

We present a comparison of techniques for estimating atmospheric emissions from fires using Australia's 2009 "Black Saturday" wildfires as a case study. Most of the fires started on Saturday the 7th of February 2009 (a date now known as "Black Saturday") and then spread rapidly, fanned by gale force winds, creating several firestorms and killing 173 people. The fires continued into early March, when rain and cooler conditions allowed the fires to be extinguished. In this study, we compare two new techniques (and one more established method) to estimate the total emissions of a number of atmospheric trace gases from these fires. One of the new techniques is a "bottom-up" technique that combines existing inventories of fuel loads, combustion efficiencies and emission factors with an estimate of burned area derived from MODIS rapid response daily fire counts. The other new method is a "top-down" approach using MODIS aerosol optical depth as a proxy for total amounts of trace gases emitted by the fires. There are significant differences between the estimates of emissions from these fires using the different methods, highlighting the uncertainties associated with fire emission estimates. These differences are discussed along with their likely causes and used as a vehicle to explore the merits of the different methods, and further constrain fire emissions in the future.

## Keywords

fires, comparison, techniques, estimating, australia, emissions, black, vegetation, saturday

## Disciplines

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# Australia’s Black Saturday fires - comparison of techniques for estimating emissions from vegetation fires

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Running title – “Black Saturday Fires - 3 emissions estimates”

Keywords: FINNv1; FEEV-AOD; GFEDV3.1; Biomass burning

# Abstract

We present a comparison of techniques for estimating atmospheric emissions from fires using Australia's 2009 "Black Saturday" wildfires as a case study. Most of the fires started on Saturday the 7th of February 2009 (a date now known as "Black Saturday") and then spread rapidly, fanned by gale force winds, creating several firestorms and killing 173 people. The fires continued into early March, when rain and cooler conditions allowed the fires to be extinguished. In this study, we compare two new techniques (and one more established method) to estimate the total emissions of a number of atmospheric trace gases from these fires. One of the new techniques is a "bottom-up" technique that combines existing inventories of fuel loads, combustion efficiencies and emission factors with an estimate of burned area derived from MODIS rapid response daily fire counts. The other new method is a "top-down" approach using MODIS aerosol optical depth as a proxy for total amounts of trace gases emitted by the fires. There are significant differences between the estimates of emissions from these fires using the different methods, highlighting the uncertainties associated with fire emission estimates. These differences are discussed along with their likely causes and used as a vehicle to explore the merits of the different methods, and further constrain fire emissions in the future.

## 1. Introduction

### 1.1 The Black Saturday Bushfires

During the first week of February 2009, the Australian state of Victoria suffered an exceptional heat-wave with temperatures in excess of 40°C for several days and hot tropical air flowing down through southeastern Australia. These weather conditions followed a severe drought in this region [*Mullen*, 2009], creating conditions of extreme fire danger in areas with an abundance of dry fuel ready to burn. On the 7th February 2009 the temperatures in

Victoria were the hottest on record; temperatures in the city of Melbourne reached 46.4°C. More than 400 separate fires broke out on this day with fallen power lines, lightning and arson the suspected ignition causes [*Teague et al.*, 2009]. A change in wind direction in the evening caused cooler winds gusting to speeds in excess of 100km $hr^{-1}$ that spread the fires at great speed back in the direction of towns that had escaped the fires earlier. Despite advanced warnings of the worst day for fire weather on record, the number of localities and different fires involved, the intensity and the speed of the fires resulted in widespread loss of life and property. A total of 173 people died during this fire event, making the Black Saturday bushfires the worst in Australia's recorded history. The fires continued to burn throughout the remainder of February and into March, when rain and cooler conditions extinguished the fires. In total, an area in excess of 450,000 hectares (4500 $km^2$) was burned between 7th February and 14th March 2009, and over 3,500 buildings were destroyed [*Teague et al.*, 2009].

Figure 1 shows images taken by the satellite-borne Moderate Resolution Imaging Spectroradiometer, (MODIS) instruments (carried on both the Terra and Aqua satellites) that capture the smoke and heat from the original firestorm on 7th February 2009 and also fires on two subsequent days in February 2009 [*Kaufman et al.*, 1990].

## *1.2 Estimating Total Emissions to the Atmosphere*

Large vegetation fires like the Black Saturday bushfires are a significant source of both trace gases and aerosols to the atmosphere. 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 that simulate atmospheric composition and air quality require estimates of the 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 [*Ito and Penner*, 2004; *Kasischke and Penner*, 2004; *van der Werf et al.*, 2006; *van der Werf et al.*, 2010]. These particular 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 from 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. Another "bottom-up" approach uses satellite measurements of fire radiative energy as a basis for estimating fuel consumed in fires and further, total emissions [*Kaiser et al.*, 2012; *Roberts et al.*, 2011; *Wooster*, 2002].

An alternative approach, described as a "top down" estimate uses satellite measurements of an atmospheric constituent emitted from biomass burning, such as carbon monoxide (CO), combined with inverse modelling to infer the source strength of emissions [*Arellano et al.*, 2006; *Pfister et al.*, 2005].

Unfortunately the uncertainties involved in estimating total emissions from fires are large. Comparisons of bottom-up emission estimates vary widely [*Al-Saadi et al.*, 2008] and estimates from top-down and bottom-up approaches have sometimes shown poor agreement [*Arellano et al.*, 2006; *Hoelzemann et al.*, 2004]. For this reason, evaluation of multiple emission estimation techniques that have different uncertainties is useful to helping constrain estimates of the emissions to the atmosphere that result from vegetation fires.

In this study we use two very different newly developed techniques to estimate total emissions of a number of different trace gases and aerosol species from the Black Saturday fires. We compare the results from the two new techniques with those estimated by the Global

Fire Emissions Database version 3 (GFEDV3.1) [*van der Werf et al.*, 2010] and use this as a vehicle for discussing the merits and limitations of the new methods compared with existing methods described in the literature.

## 2. Description of Two New Methods for Estimating Emissions

### *2.1 Bottom-Up Method using Satellite Measurements of Thermal Anomalies*

The Fire Inventory from NCAR version 1 (FINNv1) provides estimates of daily emissions from open biomass burning (wildfires, managed fires and agricultural burning) with 1km resolution and global coverage [*Wiedinmyer et al.*, 2011]. FINNv1 has been developed to meet the needs of atmospheric chemical transport modelling and chemical weather prediction and the emission estimates are available in near-real time.

Equation 1 below is used by FINNv1 for the example trace gas carbon monoxide (CO):

**Equation 1:**

$$E_{CO} = A(x,t) \times B(x) \times FB \times ef_{CO}$$

Where:

- $E_{CO}$ is the mass of example species CO emitted
- $A(x,t)$ is the area burned at time $t$ and location $x$
- $B(x)$ the biomass loading at location $x$
- $FB$ is the fraction of that biomass that is burned in the fire, and
- $ef_{CO}$ is the emission factor of example species CO (the mass of CO emitted per kilogram of dry biomass burned)

Whilst FINNv1 can use any fire detection data, the analyses described here uses observations from the MODIS instruments onboard NASA’s Aqua and Terra satellites. For this particular application, the MODIS Data Processing System (MODAPS) of Collection 5, version 5.1

[*Davies et al.*, 2009; *Giglio et al.*, 2003] was used to determine fire locations at the time of the satellite overpasses.

The vegetation type and biomass loading is taken from the MODIS Collection 5 Land Cover Type for 2005 [*Friedl et al.*, 2010] and used to determine relevant emission factors and fuel loadings [*Akagi et al.*, 2011; *Andreae and Merlet*, 2001; *Hoelzemann et al.*, 2004] as well as assigning the proportion of the 1km x 1km area that is assumed to have burned [*Wiedinmyer et al.*, 2011] and the fraction assumed to burn [*Wiedinmyer et al.*, 2006]. Explicit details describing FINNv1 may be found in *Wiedinmyer et al* [2011]. Figure 2 shows the resulting daily FINNv1 emissions of CO, gridded to $0.5^{o}$ spatial resolution for 4 example days (7 , 8, 9 and 16 February 2009).

## *2.2 Top-Down Method using Satellite Measurements of Aerosol Optical Depth*

The Fire Emissions Estimate Via Aerosol Optical Depth (FEEV-AOD) is a top-down method that utilises the strong correlations between aerosol optical depth (AOD) and column amounts of many trace gases in smoke plumes aged a few hours to one or two days [*Paton-Walsh et al.*, 2010b; *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 [*Kaufman et al.*, 1997; *Remer et al.*, 2005; *Tanre et al.*, 1997]. All grid boxes in the region of the active fires with AOD values above a threshold value are included in the calculation and assumed to result from smoke from the fires. The threshold is chosen to be typical of the highest values usually measured in the absence of a major pollution event, which in this case was chosen as 0.2. A normal background AOD amount (0.1 in this case) is subtracted from each of the identified 1° by 1° grid boxes to yield the excess AOD produced by the fires.

The excess AOD values are then translated into equivalent excess amounts of trace gases in the smoke plumes. The corresponding total column amounts of CO, hydrogen cyanide (HCN), formaldehyde ($CH_2O$), ammonia ($NH_3$), acetylene ($C_2H_2$), ethylene ($C_2H_4$), ethane ($C_2H_6$), formic acid (HCOOH) and methanol ($CH_3OH$) 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.*, 2008; *Paton-Walsh et al.*, 2005; *Rinsland et al.*, 2005]. Total column amounts are then converted to total mass of the emitted gas by multiplying by the area and the molecular weight and dividing by Avogadro's number.

The conversion for the example trace gas carbon monoxide (CO) is given by Equation 2 below:

**Equation 2:**

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

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 $\times 10^{18}$ molecules $cm^{-2}$ (the gradient of column CO to AOD determined by Paton-Walsh *et al* [2005])
- $A_{grid}$ is 1.02 $\times 10^{14}$- 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 $\times 10^{23}$ $mol^{-1}$, 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 3 shows the 1° by 1° grid averaged AOD measured by MODIS instruments on the 7th February 2009 (Black Saturday) and on the following day, 8th February 2009. The white pixels represent areas where the data has been rejected by the MODIS algorithm due to cloud interference, sea glint or other reason [*Remer et al.*, 2002]. Calculations for these two days yield identical estimates for the emitted mass of CO of 0.46 Tg on the 7th February and 0.46 Tg on the 8th February.

Clearly, parts of the plume are missed in the areas of the white pixels. Also, it is not obvious how much of the enhancements observed on the 8th February result from emissions from the 7th February that have not been dispersed from the region. The chemical transport model MOZART-4 [*Emmons et al.*, 2010] is used to model the fire emissions and dispersion of the plumes, thereby providing an estimate of the effects of double-counting and of missing data. The MOZART-4 simulation of the Black Saturday fires was run at 2.8° x 2.8° horizontal resolution, and for each day of the fires a mass of CO emissions (defined by the excess AOD detected from Equation 2) was released into the model from a 2.8° x 2.8° grid box centred at (38.57S, 146.25E). The fire-emitted 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 day's emissions and so the double-counting is estimated by summing all previous emissions still remaining in each 1° by 1° grid box included in the emissions calculation (those with an AOD > 0.2). The model output can also be used to estimate the likely magnitude of the underestimation caused by the missing data. Zhang *et al.* [2005] reported a similar method using inverse modelling of Aerosol Index constrained by measurements made by the Total Ozone Mapping Spectrometer however AOD has the advantage of being independent of the height of the plume. A more detailed description of the FEEV-AOD method is provided by Paton-Walsh *et al* [2010a].

# 3. Comparison of Total Emissions of trace gases from the “Black Saturday” Fires

## *3.1 Emissions estimates from the Black Saturday fires using three methods*

The total emissions from the Black Saturday fires of a number of different species were estimated by the three different methods (FINNv1, FEEV-AOD and GFEDV3.1) and are shown in Table 1. The emissions estimates for the two new techniques were limited to the 28 days of February 2009 for the sake of comparison to the GFEDV3.1 monthly emissions value. The FINNv1 and GFEDV3.1 totals were extracted for the region from 34S, 135E to 44S, 151E, whilst FEEV-AOD utilised a larger area from 34S, 135E to 48S, 165E. This larger area extends over a greater area of sea but does not include any more land area, thereby allowing more chance of capturing the enhance AOD in the travelling smoke plumes without sampling a larger landmass (see Figure 3).

Carbon dioxide ($CO_2$) is not currently estimated by FEEV-AOD, so CO is the most predominant emission that is estimated by all three methods. The estimates for CO from the new techniques fall to either side of the GFEDV3.1 estimates, with the top-down method (FEEV-AOD) approximately 50% higher and the new bottom-up method (FINNv1) approximately 3 times lower (Table 1).  A similar pattern of differences is also seen for some of the minor emissions, with FINNv1 consistently lower than GFEDV3.1, and FEEV-AOD typically around 50% higher (e.g. for gases $CH_3OH$ and $CH_2O$). In contrast, GFEDV3.1 reports higher values than FEEV-AOD for $NH_3$, $C_2H_4$ and $C_2H_6$, revealing differences in the characterisation of emission factors in these two methods.

### *3.2 Potential biases in estimates from FINNv1 compared to other methods*

Fire detection in FINNv1 depends solely upon satellite derived thermal hotspots (to enable delivery of near-real time daily emissions values), whilst in GFEDV3.1 thermal hotspot data are used only to supplement satellite-derived estimates of area burned from MODIS [*Giglio et al.*, 2010; *van der Werf et al.*, 2010]. Thus, reduced fire detection (e.g. as a result of cloud cover) provides one possible explanation for much lower estimates from FINNv1 as compared to GFEDv3.1.

This theory was examined by comparing the total dry biomass consumed and the total burned areas predicted by FINNv1 and GFEDv3.1. The comparison showed that GFEDv3.1 estimated approximately 2 times higher area burned (downloaded from fuoco.geog.umd.edu), and a factor of 2.5 higher dry biomass burned (from http://www.falw.vu/~gwerf/GFED/GFED3/emissions/) than that estimated by FINNv1. More than 90% of the fires in both models occur in forested landscapes. Therefore, the primary difference between the models is missed burned area in FINNv1, highlighting the lack of robustness in the use of rapid response fire detections by FINNv1. These differences were compounded to some extent by lower amounts of dry biomass consumed per unit area burned in FINNv1 compared to GFEDv3.1.

It is worth remembering that the Black Saturday fires were truly exceptional with the preceding drought having built up large amounts of dry fuel ready to burn and the most extreme fire conditions on record [*Mullen*, 2009; *Teague et al.*, 2009]. These details of the local conditions at the time are beyond the scope of the land cover type inventories used to determine relevant fuel loadings applied by FINNv1 (which are based on earlier years) [*Friedl et al.*, 2010; *Friedl et al.*, 2002; *van der Werf et al.*, 2010; *Wiedinmyer et al.*, 2011]. Underestimation of the fuel loading for the vegetation type in which the fires burned can result in an underestimation of fire emissions, and can an underestimation of the fraction of fuel burned.

There are also significant differences between FINNv1 and FEEV-AOD in the proportion of the total emissions designated to each day (see Figure 4). Note that the GFEDV3.1 emissions are given as a monthly composite value. FEEV-AOD estimates that a higher proportion of the emissions were released on Black Saturday itself and much greater emissions for the following day (8 February 2009). The huge discrepancy for the 8 February supports the idea that FINNv1 underestimated the extent of the fires due to significant cloud interference at the time of the satellite overpasses (Figure 5). Another contributing factor to these differences is that FEEV-AOD will have assigned to 8 February smoke detected from fires that burned on 7 February after the satellite overpasses. In fact, the largest enhancement in AOD is detected on 8 February, and only the adjustment for non-dispersed smoke made by FEEV-AOD reduces the estimated emissions for 8 February below the value for 7 February.

The nitrogen species (e.g. $NH_3$ and NO) are proportionally even lower in FINNv1 suggesting different emission factors are assumed in the models.

### 3.3 Potential biases in estimates from FEEV-AOD compared to other methods

The level of agreement between estimates from FEEV-AOD and GFEDV3.1 are just within the expected uncertainties for most gaseous emissions. The better agreement between these two methods may be due to a smaller influence from cloud cover. The reliance of GFEDV3.1 on burned area products makes this method very much less sensitive to cloud-interference than FINNv1, whilst the atmospheric lifetime of aerosol optical depth (of ~3.8 days [*Edwards et al.*, 2006]) also makes it less likely that a fire will be missed altogether as a result of clouds in FEEV-AOD. The ~50% higher values estimated for the emissions of CO, $CH_3OH$ and

$CH_2O$ by FEEV-AOD could result from any combination of the uncertainties inherent in the two methods, including inaccuracies in the modelled dispersions resulting in double counting of the emissions in FEEV-AOD. Another potential bias comes from the choice of threshold and average values used for AOD at 500nm. These are estimated from measurements before and after the fire event, and are thus dependent upon the exact time chosen. A sensitivity test using the largest reasonably justifiable values (0.24 for the threshold value and an average value of 0.15) yielded a result ~ 50% lower in excellent agreement with GFEDV3.1. Alternatively the lower GFEDV3.1 estimates could indicate that the assumed fuel loads have not accounted sufficiently for the large build up for dry fuel at the ground reported by *Mullen et al.* [2009].

On the other hand, the estimates from FEEV-AOD could be high as a result of increased uncertainties due to the atypical nature of the fires. FEEV-AOD infers the total column amounts of trace gases in the smoke plumes via relationships to ground based measurements of AOD. The use of MODIS AOD requires an assessment of the biases between this satellite AOD product and the ground-based AOD, which was determined to be 27% ± 23% from coincident highly enhanced AOD values over the area [*Paton-Walsh et al.*, 2010a]. The Black Saturday fires caused extreme firestorms that injected significant material into the stratosphere [*Siddaway and Petelina*, 2011], and thus the comparative viewing geometry will be different for these fires potentially causing a larger bias in an already highly uncertain factor.

GFEDV3.1 reports higher values than FEEV-AOD for $NH_3$, $C_2H_4$ and $C_2H_6$ revealing differences in the characterisation of emission factors in these two methods. FEEV-AOD is based upon ratios between AOD and trace gases made in smoke aged for a number of hours and hence may underestimate the true $NH_3$ emissions (since the $NH_3$ is likely to be lost from the atmosphere much more rapidly than the AOD), thereby providing a plausible explanation for the different estimates for this gas. The differences in $C_2H_4$ are within the expected uncertainties however there is evidence that $C_2H_6$ emissions from Australian eucalyptus forests are significantly lower than from temperate forests elsewhere in the world [*Paton-Walsh et al.*, 2005] and this detailed local information is not included in the GFEDV3.1 method.

## 4. Summary and Conclusions

Australia's 2009 "Black Saturday" wildfires have been used as a case study to compare emissions estimates from two new methods (FINNv1 and FEEV-AOD) with estimates from GFEDV3.1. The "top down" method using MODIS AOD measurements (FEEV-AOD) agrees with GFEDV3.1 within the expected uncertainties for most gases that are estimated by both methods except for $C_2H_6$. We conclude that the use of elevated AOD as a means of inferring total emissions from fires is promising, with its relatively short-lifetime making it a reliable marker of fresh smoke. However, currently the utility of this technique is limited since it has not been developed sufficiently to produce operational global emissions estimates.

Estimates of emissions from the Black Saturday fires from FINNv1 are significantly lower than those from GFEDV3.1. The reliance on thermal hotspots alone makes FINNv1 susceptible to underestimation of fires in the presence of clouds and the use of an extreme event such as the Black Saturday fires may accentuate these problems. Uncertainties in these emissions estimates are large and the agreement is much better when comparisons are made over large spatial and temporal scales [*Wiedinmyer et al.*, 2011]. FINNv1 provides a much needed high temporal and spatial emissions inventory that is available in near-real time and can be used for chemical weather forecasting.

The comparison described here also highlights the difficulty of modelling correct fuel loadings especially in forested areas where the build-up of dry fuel may be hidden from the view of satellites by the forest canopy. There may be a fundamental limit to the accuracy of such models without significant extra requirements for input of data gathered at ground level.

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**Table 1: Comparison of total emissions estimates for a number of species from the Black Saturday fires by 3 different techniques**

| Compound | Mass emitted (Gg) –FINNv1* | Mass emitted (Gg) – FEEV- AOD | Mass emitted (Gg) – GFEDV3.1* |
|---|---|---|---|
| $CO_2$ | 7240 | | 18000 |
| CO | 405 | 1700 ± 500 | 1200 |
| Organic Carbon | 21 | | 98 |
| $CH_4$ | 22 | | 55 |
| $CH_3OH$ | 8.8 | 30 ± 10 | 22 |
| $CH_2O$ | 6.6 | 30 ± 10 | 21 |
| $C_2H_6$ | 2.6 | 4 ± 1 | 8.3 |
| $C_3H_6$ | 2.5 | | 7.0 |
| $C_2H_4$ | 4.1 | 11 ± 3 | 14 |
| $C_2H_2$ | 1.0 | 4 ± 1 | |
| HCOOH | 2.2 | 24 ± 7 | |
| HCN | 1.6 | 6 ± 2 | |
| TOLUENE | 20 | | 13 |
| $NH_3$ | 3.4 | 13 ± 4 | 19 |
| $NO_X$ | 11 | | 38 |
| $CH_3CHO$ | 6.0 | | 6.3 |
| $SO_2$ | 2.0 | | 11 |
| Black Carbon | 2.3 | | 6.4 |

*rounded to two significant figures

## *Figure Captions:*

**Figure 1: MODIS visible images and thermal anomalies (red pixels) show where fires are burning on the 7th February 2009 (upper panel) 9th February 2009 (lower left panel) and 16th February 2009 (lower right panel).**

**Figure 2: Emissions of CO (in molecules.cm$^{-2}$.s$^{-1}$) shown on a 0.5° x 0.5° grid for each day from 7 February to 9 February 2009 and also on 16 February. The emissions are colour coded by intensity with the largest emissions in red. Zero emissions are shown as white.**

**Figure 3: 1° by 1° grid averaged AOD measured by MODIS instruments on the 7th February 2009 (Black Saturday) and on the following day, 8th February 2009.**

**Figure 4: Daily total mass of CO (Gg) emitted from fires in the region 34S, 135E to 44S, 151E estimated for each day of February 2009 by FINNv1 and FEEV-AOD.**

**Figure 5: MODIS visible image and thermal hotspots for 8 February 2009 over south-eastern Australia showing both smoke from the fires and significant cloud cover.**

Figure 1:

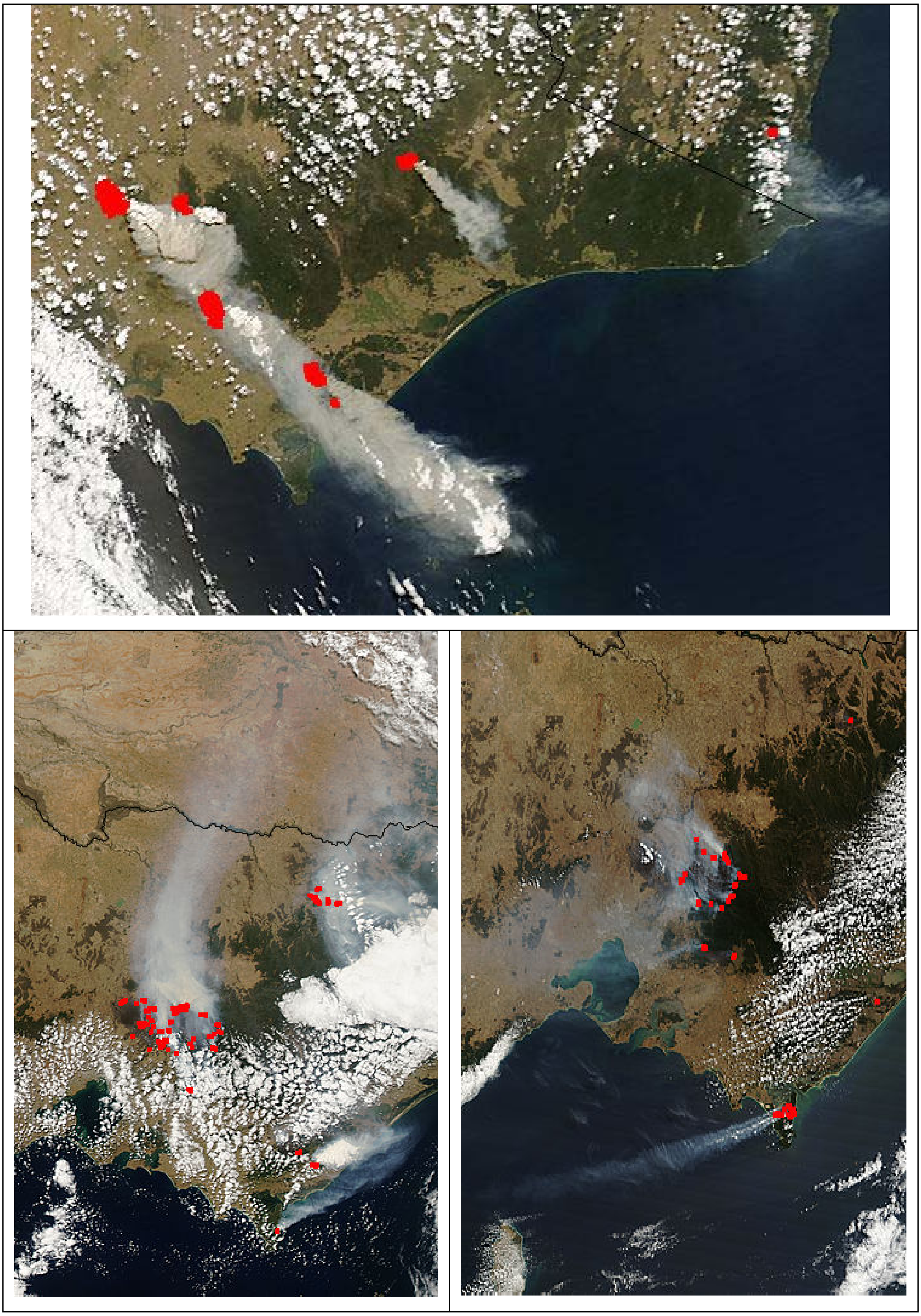
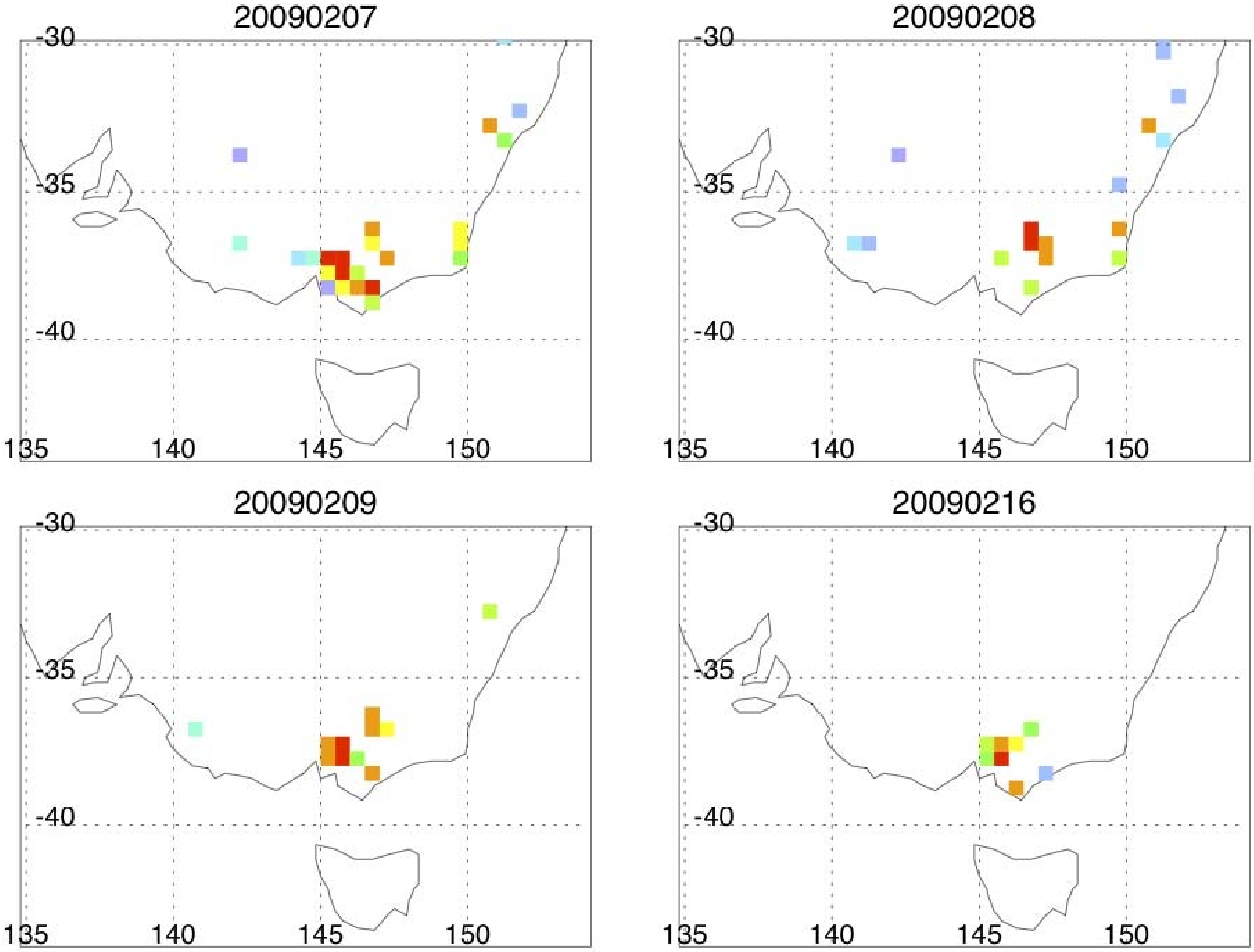


Figure 2:


20090207
-30
-35
-40
135
140
145
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20090208
-30
-35
-40
135
140
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20090209
-30
-35
-40
135
140
145
150
20090216
-30
-35
-40
135
140
145
150

Figure 3

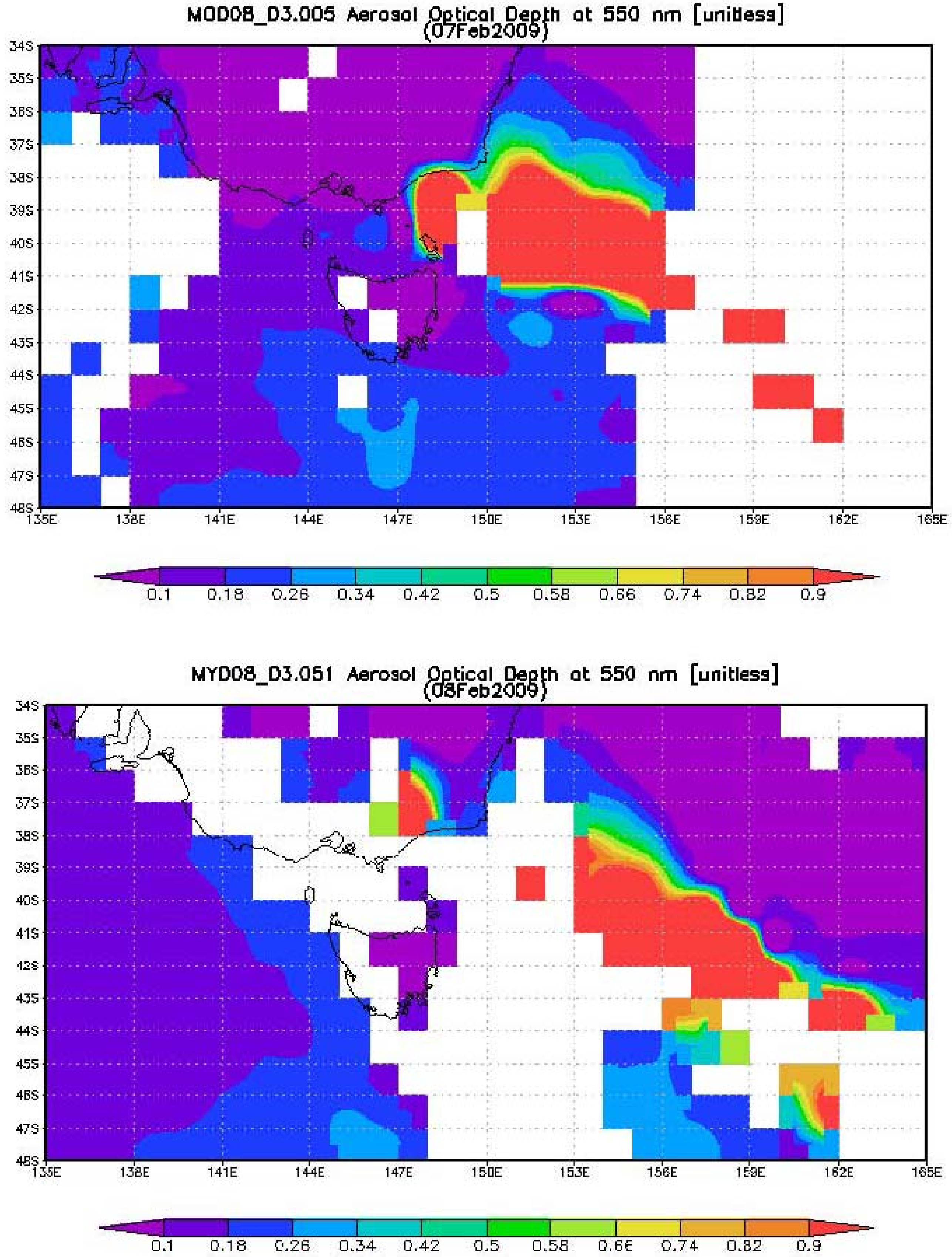
MOD08_D3.005 Aerosol Optical Depth at 550 nm [unitless]
(07Feb2009)
34S
35S
36S
37S
38S
39S
40S
41S
42S
43S
44S
45S
46S
47S
48S
135E
138E
141E
144E
147E
150E
153E
156E
159E
162E
165E
0.1
0.18
0.26
0.34
0.42
0.5
0.58
0.66
0.74
0.82
0.9
MYD08_D3.051 Aerosol Optical Depth at 550 nm [unitless]
(08Feb2009)
34S
35S
36S
37S
38S
39S
40S
41S
42S
43S
44S
45S
46S
47S
48S
135E
138E
141E
144E
147E
150E
153E
156E
159E
162E
165E
0.1
0.18
0.26
0.34
0.42
0.5
0.58
0.66
0.74
0.82
0.9

Figure 4:

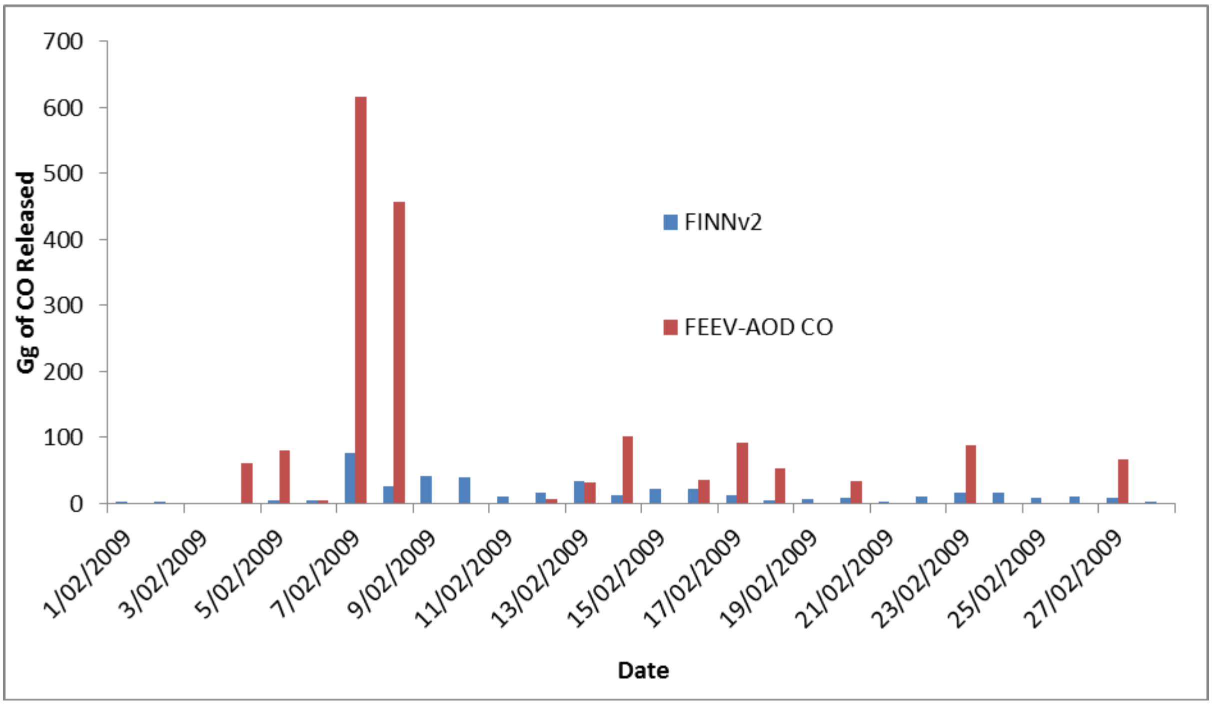

Figure 5: