

MODELLING FINE PARTICULATE MATTER OVER DARWIN (AUSTRALIA) DUE TO EXTENSIVE SAVANNAH BURNING DURING 2003–2007

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1. INTRODUCTION

Atmospheric particulate matter, or aerosol, is important from an air quality and health perspective as well as in the science of climate change. According to the database GFEDv2 (van der Werf et al., 2006), the global annual biomass burning emissions of total particulate matter and PM_{2.5} (particulate matter with an aerodynamic diameter of 2.5 microns or less), averaged over the years 1997–2006, were 50 Tg and 37 Tg, respectively. Of these, the Australian contributions were 5.5% and 4.6%, respectively, most of which resulted from wild fires and prescribed fires in the savannah region of northern Australia.

Recently, Meyer et al. (2008) determined emissions of biomass burning aerosol across the Top End — the monsoonal top half of the Australian Northern Territory within which the city of Darwin is located — constrained by aerosol measurements, for the dry season April–November 2004 at a high spatiotemporal resolution (1 km, 1h). The emission methodology used a fuel-load distribution map, satellite-derived imagery of fire scars and hot spots, and the diurnal variation of a fire danger index. These emissions were verified by Luhar et al (2008) in a transport model called TAPM (see Hurley et al., 2005) and by comparing the modelled PM_{2.5} concentrations and aerosol optical depth with measurements. Here, we extend the above work to five years (2003–2007), thus deducing information on the inter-annual variability of emission patterns and consequently of air quality as measured in terms of PM_{2.5} concentration. We also use new and more robust modelling options (e.g. gravitational settling and deposition). The calculated emissions are compared with those from other methods, and the modelled concentrations are compared with ground-based measurements taken around Darwin. We also make a preliminary estimate of the influence of chemistry in bushfire plumes on aerosol concentrations by employing a comprehensive chemical transport model (CTM) for a selected period.

2. EMISSION CALCULATION

The same spatial distribution of fuel load (kg C ha⁻¹) for the Top End as derived by Meyer et al. (2008) at a grid resolution of 1 km × 1km was used (Figure 1). The main tool used in deriving the fuel load is a semi-empirical model known as VAST (Vegetation and Soil carbon Transfer) (see Barrett, 2002; Meyer et al., 2008).

VAST is a biogeochemical production model relating the main drivers of production, intercepted radiation, temperature, soil moisture, rainfall, and vegetation class, to biomass and soil pools of carbon. The fuel load is coupled with satellite data for fire scars and hotspots in order to determine the amount of fuel burned within a grid cell.

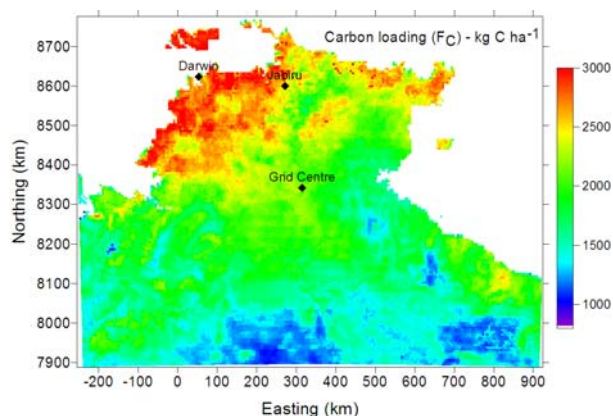


Figure 1: Spatial distribution of available fuel carbon loading (kg C ha⁻¹) in the Top End of Australia at a resolution of 1 km × 1 km (Meyer et al., 2005).

The following satellite data for the period 2003–2007 were analysed to determine the fire emissions on a daily basis: 1) fire scars (or burned areas) at a grid resolution of 1 km × 1 km as reported by the Department of Land Information (DLI) of Western Australia (now Landgate) based on NOAA-AVHRR (Advanced Very High Resolution Radiometer) satellite images, and 2) hotspot data at 1 km × 1 km resolution from Sentinel — a national bushfire monitoring system managed by Geoscience Australia — based on MODIS (Moderate Resolution Imaging SpectroRadiometer) on the Terra/Aqua satellites.

The fire-scar data were available at a frequency of approximately once every ten days, whereas the hot-spot data were available at a frequency of once per day. The fire scars yielded burnt area, whereas the hotspots were used to derive timing information on daily basis. Prediction of emissions at hourly time resolution is enabled by assigning a diurnal variation based on a McArthur fire danger meter (see Meyer et al., 2008).

The available fuel load (derived using VAST) and the fire-scar area were used to determine the fuel burnt. An emission factor of 4.54 g PM_{2.5} per kg of dry fuel burned for savannah and grassland was applied (Ito and Penner, 2004).

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Figure 2 presents the derived total emissions of PM_{2.5} from the Top End for the years 2003–2007. A clear inter-annual variation is evident: the highest emissions were in the year 2004, followed by a dip in 2005 and an increasing trend for the subsequent two years. The second highest emissions were for 2007.

Table 1 gives the estimated total amounts of dry matter burned and carbon released into the atmosphere besides the total PM_{2.5} emissions. The total carbon emission for the full year 2004 is 69.3 Tg, which can be compared to 67.6 Tg obtained by Meyer et al. (2008) for April–November for the same year. As noted by them, this figure is in remarkable agreement with the bulk estimate of 64.3 Tg derived using the ANGGI (Australian National Greenhouse Gas Inventory) methodology (AGO, 2007). Emissions of aerosols and other species can be calculated from the dry matter burned or from the carbon emitted by applying appropriate emission factors.

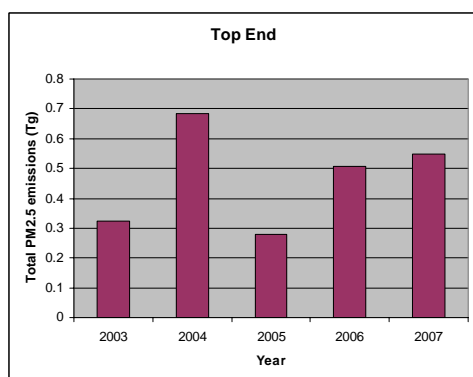


Figure 2: Calculated total emissions of PM_{2.5} (Tg) from the Top End for the years 2003–2007.

Table 1: Estimates of biomass combustion in the Top End.

Year	Dry matter burned (Tg)	Carbon released (Tg)	PM _{2.5} released (Tg)	GFEDv2 Carbon released ¹ (Tg)
2003	71.6	32.9	0.325	23.5
2004	150.7	69.3	0.684	57.5
2005	61.2	28.2	0.278	23.2
2006	111.9	51.5	0.508	45.0
2007	120.7	55.5	0.548	-

¹Based on figures from the GFEDv2 database (see van der Werf et al. (2006); data downloadable from <http://ess1.ess.uci.edu/~jranders/data/GFED2>).

For comparison purposes, Table 1 also presents the total amounts of carbon released from the Top End for the years 2003–2006 determined from the Global Fire Emissions Database (GFEDv2) given at a spatial resolution of 1° × 1° and a temporal resolution of

8 days (see van der Werf et al., 2006). The GFEDv2 emission methodology also makes use of satellite data for burned areas and a biogeochemical model for fuel loads. Our estimates are consistently higher than those from GFEDv2 by 13–28%, but the similarity between the annual variations of the emission from the two datasets is remarkable, considering the fact that the two methodologies are independent with uncertainties in fuel loads and other combustion parameters, and differences in the way the satellite data have been used. However, note that our approach involves a much finer spatial and temporal resolution (1 km, 1h) with the emissions constrained by ambient aerosol concentration measurements.

Time series of the estimated daily PM_{2.5} emissions (tonnes per day) presented in Figure 3 for the five years show that biomass burning starts in April and ends in November–December. The most intense emissions occur from September onwards, except for the low emission year of 2005 when they occur in April–May.

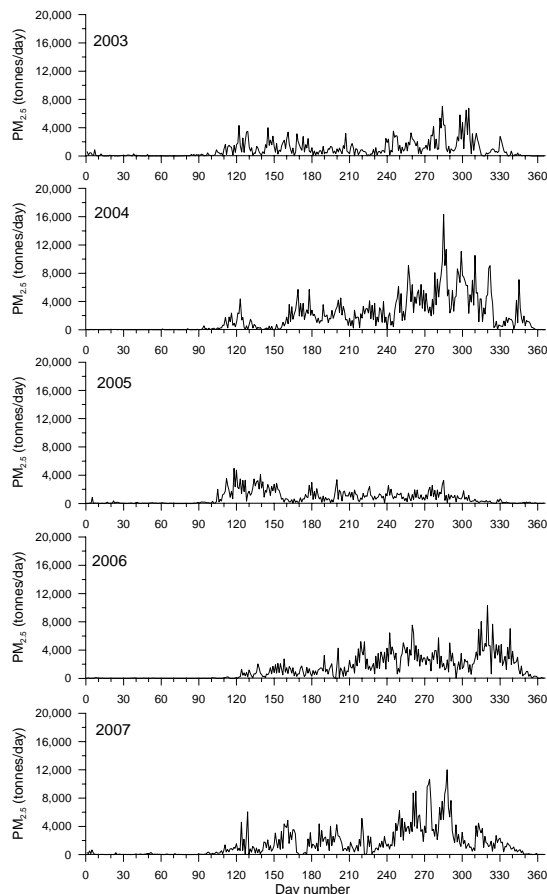


Figure 3: Calculated time series of daily PM_{2.5} emissions (tonnes per day) from the Top End the years 2003–2007.

The calculated spatial distribution of PM_{2.5} emissions suggests (plots not shown) that they are negligible during January–February, with a small increase in biomass burning during March–April in the

western/north-western part of the Top End (except for the period in 2006 during which the emissions are negligible). During May–June, emissions increase, but are largely confined to the north-west of the region. Emissions extend to the east and north-east during July–August. For September–October, except of the year 2005, southern areas also burn, but their emission intensities are not as high as those in the north. During November–December, the fire activity in the north subsides, but large areas in the south continue to release aerosols (except for the year 2005).

3. MODELLING AEROSOL CONCENTRATIONS

We apply a three-dimensional prognostic meteorological and transport model called TAPM (v3.5) (Hurley et al., 2005) to predict aerosol concentrations across the Top End. The model inputs include synoptic analyses, and databases of terrain height, land use, and monthly sea-surface temperature.

We select a horizontal model domain of 1000 km × 1000 km centred at the location (133°17' E, 15°0' S), with a grid resolution of 10 km × 10 km. The vertical model levels are staggered, with the lowest ten of the 20 vertical levels used being 10, 50, 100, 150, 200, 300, 400, 500, 750 and 1000 m above the ground level and the highest model level being 8 km. The values of the deep soil volumetric moisture content for the months January–December were 0.2, 0.2, 0.15, 0.1, 0.05, 0.05, 0.05, 0.05, 0.05, 0.05, 0.1 and 0.15, respectively, with a value of 0.05 reflecting dry conditions. The input synoptic meteorological fields were obtained from the Australian Bureau of Meteorology's GASP (Global Analysis and Prediction) analyses given at 6 hourly intervals with a horizontal grid resolution of 1° × 1°.

The input hourly PM_{2.5} emissions rates determined earlier at a resolution of 1 km × 1 km were averaged over the model resolution. TAPM was run with the gravitational settling and deposition option.

3.1 Comparison with Data

Measurements of aerosols made at the Casuarina Campus site of the Charles Darwin University for the period 1 May – 31 October 2007 were used for comparison with the model simulations. Both PM_{2.5} and PM₁₀ were measured using a Partisol Dichotomous air sampler, and PM₁₀ was also measured using a Tapered Element Oscillating Microbalance (TEOM).

Figure 4a shows the time series of the 24-hour averaged (or daily) observed concentration of PM_{2.5}. The advisory Air NEPM of 25 µg m⁻³ for the daily PM_{2.5} is exceeded on three occasions.

A linear regression between the observed PM_{2.5} and the observed PM₁₀ suggests that the ambient aerosol is most likely due to biomass burning, and that around 12% of PM₁₀ is not included in the PM_{2.5} fraction, or equivalently, that on average 88% of PM₁₀ due to biomass burning consists of PM_{2.5}. The intercept value of 5.9 µg m⁻³ of the regression line can be considered as a background PM₁₀ component in the size range 2.5 –

10 µm that may be due to non-biomass burning sources such as maritime haze and mineral dust.

In Figure 4a, the modelled time series of the daily PM_{2.5} concentration is in good agreement with the data, with the model performing reasonably well at predicting the observed peaks.

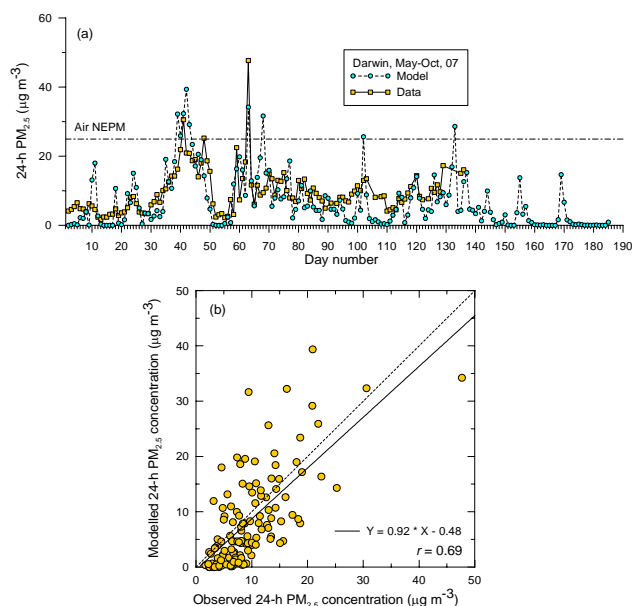


Figure 4: (a) Time series of the observed and modelled 24-hour averaged PM_{2.5} concentrations at Darwin for the period 1 May – 31 October 2007, and (b) scatter plot of the observed and modelled 24-hour averaged PM_{2.5} concentrations.

The model tends to underpredict the lower concentrations, which may be partly because non-biomass burning sources such as background maritime haze, mineral dust and other pollution sources (e.g. motor vehicles), although much less dominant, also contribute to PM_{2.5} concentrations. In addition, possible generation of secondary organic aerosols, neglected in the modelling, may be a significant contributor. Less likely reasons include the inability of the model to account for the possible recirculation of particulate matter once it leaves the model domain and for contributions from sources outside the model domain; a larger-scale model will need to be considered to address these issues.

The model overpredicts some of the higher concentration values, and as a result gives a higher number of exceedences of the Air NEPM than the observed: 8 as opposed to 3.

Departure of the modelled wind direction from that observed, which may be due to model approximations and parameterisations as well as the quality of input data including synoptic analyses, can also result in a modelled concentration being substantially different from the observed one at the same time and location, especially when only a few

scattered sources are present. The resolution (10 km × 10 km) used in the model is rather coarse, and a finer resolution may have improved the predictions. A proper accounting of plume rise in the model may have also led to better predictions.

A scatter plot between the observed and modelled concentrations is presented in Figure 4b. The correlation coefficient is $r = 0.69$ and the slope of the best fit line is 0.92. This model performance is better than that reported in Luhar et al. (2008) for the year 2004.

In the quantile-quantile plots in Figure 5, the sorted modelled daily concentrations of $PM_{2.5}$ are plotted against the sorted daily observed values (i.e. independent of time) at Darwin for the bushfire period over four years (there were no measurements available for the year 2003). A q-q plot compares the distributions of two data sets, and highlights any bias of the model over the observed distribution. TAPM tends to underestimate the lower concentrations, which may be due to the neglect of any background fine aerosol (as discussed earlier). The model setup performs satisfactorily for the higher concentrations, except for the year 2005.

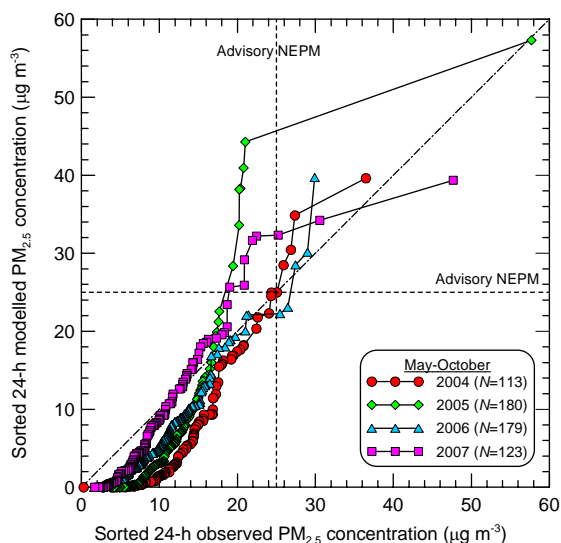


Figure 5: Quantile-quantile plots of the modelled vs. observed 24-h averaged concentrations at Darwin for the period May–October given for four years. The N values are the number of valid data points.

The modelling reveals that most exceedences of the Advisory NEPM for the daily $PM_{2.5}$ in the north-west of the Top End, which includes Darwin, occur during early to mid part of the burning season. One reason for the high number of exceedences in the north-west is its high fuel load. The predicted and observed number of exceedences can be deduced from Figure 5 for a particular year. The model substantially overpredicts the number of the exceedences for the years 2005 and 2007.

3.2 Modelling Secondary Aerosols and Ozone

The above model simulations included deposition losses but did not involve any chemical transformation. Chemical reactions can occur during plume transport, leading to the formation of secondary gaseous species such as ozone and secondary inorganic and organic aerosol species. In this section, we describe a preliminary application of the model TAPM-CTM that includes chemistry to predict aerosol and ozone concentrations across the Top End. The chemical-transport modelling component uses:

- The same emission inventory as describe above but with extensions for natural aerosols such as sea salt and biogenic emissions of volatile organic compounds.
- A chemical transport model (CTM) (Cope et al., 2004), coupled with the Carbon Bond 2005 mechanism for modelling photochemical transformation.
- A secondary organic aerosol (SOA) module.
- A model for an Aerosol Reacting System for modelling secondary inorganic $PM_{2.5}$ production.

Figure 6 shows a comparison of the observed and modelled 24-h $PM_{2.5}$ concentrations in Darwin from May to October 2007. The modelled $PM_{2.5}$ concentrations have been generated using TAPM-CTM with and without chemistry. The concentrations modelled with the chemistry mode on are higher than those without, indicating that at least some of the $PM_{2.5}$ mass observed in Darwin may be secondary aerosol formed in the smoke plume during transport. The differences are relatively more significant at higher atmospheric $PM_{2.5}$ concentration when major smoke events occur. On days of lower $PM_{2.5}$ concentrations both models tend to underpredict in comparison to the observed concentrations (as was discussed previously).

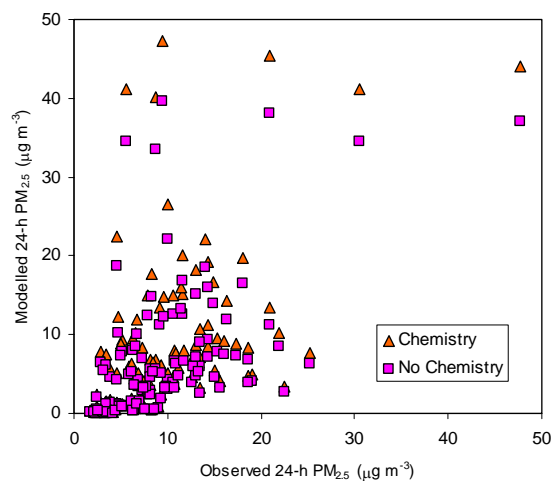


Figure 6: Scatter plots of the observed and TAPM-CTM 24-hour averaged $PM_{2.5}$ concentrations for the period May–October 2007.

The accuracy of the CTM in-plume ozone generation predictions for Darwin can be assessed by comparing the observed and modelled ozone enhancements during smoke incursions (Figure 7). There is a positive correlation between the PM_{2.5} and ozone observations. This is also seen in the modelled concentrations; however, in the latter, the ozone levels are overpredicted. However, there is a possibility that the reported ozone measurements involved some calibration issues, which need further investigation together with the current TAPM-CTM implementation.

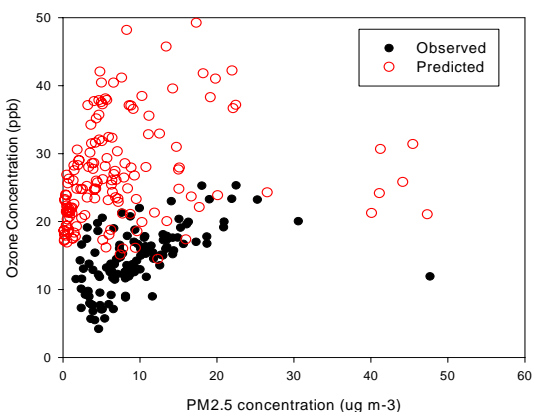


Figure 7: Relation between the observed 24-hour mean PM_{2.5} and ozone concentrations at Darwin between May and October 2007 (closed circles), and the modelled concentrations from TAPM-CTM (open circles).

4. CONCLUSIONS

Aerosol emissions from biomass burning in the Top End (which includes Darwin) for five years 2003–2007 were estimated at a high spatiotemporal resolution. The highest PM_{2.5} emissions were for the year 2004 (0.68 Tg) and the lowest for the year 2005 (0.28 Tg). Modelling of PM_{2.5} concentrations was carried out using TAPM. The results have shown satisfactory fits between the observed and modelled concentrations, suggesting that the emission methodology and the modelling are reasonably valid.

The modelling suggests that in the north-west of the Top End, most exceedences of PM_{2.5} generally occur during early to mid part of the burning season. One reason for the high number of exceedences in the north-west (including Darwin) is its high fuel load. The highest exceedences were determined to be in the early part (May–June) of the period modelled, except for the year 2006. The modelling confirms that the surface air quality in Darwin is determined largely by fires within 100 km and less impacted by longer-range transport. Also, within the region considered, there are numerous locations of extremely poor air quality, particularly in the south west during the mid fire season and in the south east during the late fire season. However these regions are sparsely populated.

Preliminary results for inclusion of reactive chemistry indicate secondary organic aerosol formation as well as a relationship between ozone formation and

PM_{2.5} concentrations. Further development of the model needs to be considered to investigate potential management scenarios to minimize smoke impacts on air quality in population centres. To assess smoke impacts on population health, additional information on people's activities is required.

TAPM predictions of PM_{2.5} presented in this study indicate that the development of similar fuel- and emission-calculation tools for Australian vegetation in other regions is feasible.

5. ACKNOWLEDGEMENTS

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