Seasonal Variation and Ecosystem Dependence of Emission Factors for Selected Trace Gases and PM2.5 for Southern African Savanna Fires

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Seasonal variation and ecosystem dependence of emission factors for selected trace gases and PM$_{2.5}$ for southern African savanna fires


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In this paper we present the first early dry season (early June–early August) emission factor measurements for carbon dioxide (CO$_2$), carbon monoxide (CO), methane (CH$_4$), nonmethane hydrocarbons (NMHC), and particulates with a diameter less than 2.5 μm (PM$_{2.5}$) for southern African grassland and woodland fires. Seasonal emission factors for grassland fires correlate linearly with the proportion of green grass, used as a surrogate for the fuel moisture content, and are higher for products of incomplete combustion in the early part of the dry season compared with later in the dry season. Models of emission factors for NMHC and PM$_{2.5}$ versus modified combustion efficiency (MCE) are statistically different in grassland compared with woodland ecosystems. We compare predictions based on the integration of emission factors from this study, from the Southern African Fire-Atmosphere Research Initiative 1992 (SAFARI-92), and from SAFARI-2000 with those based on the smaller set of ecosystem-specific emission factors to estimate the effects of using regional-average rather than ecosystem-specific emission factors. We also test the validity of using the SAFARI-92 models for emission factors versus MCE to predict the early dry season emission factors measured in this study. The comparison indicates that the largest discrepancies occur at the low end (0.907) and high end (0.972) of MCE values measured in this study. Finally, we combine our models of MCE versus proportion of green grass for grassland fires with emission factors versus MCE for selected oxygenated volatile organic compounds measured in the SAFARI-2000 campaign to derive the first seasonal emission factors for these compounds. The results of this study demonstrate that seasonal variations in savanna fire emissions are important and should be considered in modeling emissions at regional to continental scales.

INDEX TERMS: 0305 Atmospheric Composition and Structure: Aerosols and particles (0345, 4801); 0365 Atmospheric Composition and Structure: Troposphere—composition and chemistry; 1610 Global Change: Atmosphere (0315, 0325); KEYWORDS: seasonal fire emissions, savannas, southern Africa, emission factors


1. Introduction

Savanna fires are an important ecosystem process in southern Africa, with significant implications for regional and global atmospheric chemistry and biogeochemical cycles [Scholes et al., 1996; Frost, 1996]. The majority of fires in southern Africa occur typically during the dry season, from May to October. There are significant interannual variations in the magnitude and location of biomass burning emissions at the regional scale, in response to the seasonal variability that occurs at a different rate from year to year [Barbosa et al., 1999]. However, only a few studies have looked at the seasonality of fire emissions [Hoffa et al., 1999; Justice et al., 2002; Korontzi et al., 2003]. Emission factors for pyrogenically produced atmospheric species are among the information required for emissions modeling. Thus far, regional fire emissions calculations in southern Africa have been mainly based on late dry season (August–October) ground-based and airborne measurements of emission factors [Ward et al., 1996; Hao et al., 1996; Cofer et
between trees and grasses.

Fire is also used to maintain the competitive balance to have higher intensities and be presumably more destructive. Fire is used to prevent late dry season fires which tend to be more intense, and to increase the palatability of grasses for their cattle; fire is used in national parks as a management tool for rapid nutrient release prior to the new growing season by regrowth of palatable grasses; fires are used in the early part of the dry season to stimulate Wetter burns produce lower fire intensities and result in less smoke production. Pilots have advocated this approach as a land management tool [Russell-Smith et al., 1997; Bucini and Lambin, 2002].

Figure 1. Seasonal and interannual TRMM active fire distribution in southern Africa in the main dry season (May–October).

2. Methods

2.1. Site Description

The field site and fires used for the 1996 study of early dry season fire emission measurements are reported in detail by Hoffa et al. [1999]. The field site was located about 7.5 km southeast of Kaoma, Western Province, Zambia in the Kaoma Local Forest 310 (14°52’S, 24°49’E at approximately 1170 m). Thirteen 2-ha plots (100 m x 200 m) were burned between 5 June and 6 August 1996. Six plots were in a semideciduous, open canopy, semiarid woodland (miombo) and seven in a seasonally flooded grassland (dambo). The ecosystem sites were separated by approximately 500 m and a dirt road. Three distinct sampling clusters were equally spaced along the long axis of each 2-ha plot, as described by Hoffa et al. [1999].

Miombo is used to describe the central, southern and eastern African woodlands, dominated by the genera Brachystegia, Julbernardia and/or Isoberlinia [Frost, 1996]. It covers more than 2.7 million km² of Africa and 80% of Zambia. Miombo woodlands receiving less than 1100 mm rain annually are considered semiarid [Chidumayo, 1987]. Fire spread in the miombo ecosystem is largely dependent on the amount of grass cover, coupled with meteorological parameters (i.e., wind speed, relative humidity and temperature). Grass production is high in areas of low woodland cover or where the land cover has been disturbed by, for example, gardening or charcoal making. Leaf litter and downed wood are likely the major components of the fuel in the undisturbed miombo. Fires in the humid miombo ecosystem tend to be more frequent and burn with higher fire intensities, presumably due to higher fuel loads [Frost, 1996]. Dambos are distinctive areas of African grassland produced by seasonal flooding; they occupy about 10% of Zambia [Hoffa et al., 1999]. Dambos play an important role in traditional land use systems in Africa. They are mainly used for grazing, cultivation of food and cash crops, and as a water supply for domestic use and livestock [Acres et al., 1985].

2.2. Measurement of Emissions

SAFARI-2000 results showed that the composition of smoke from savanna fires changes rapidly as the smoke contains...
ages [Hobbs et al., 2003]. In the 1996 study we measured the initial emissions from grassland savanna and miombo woodland fires for carbon dioxide (CO$_2$), carbon monoxide (CO), methane (CH$_4$), nonmethane hydrocarbons (NMHC) and particulate matter with diameter less than 2.5 µm (PM$_{2.5}$). The sampling design at each plot and the emissions analyses are described by Shea et al. [1996], Ward et al. [1996], and Hao et al. [1996]. A Fire-Atmosphere Sampling System (FASS) tower was placed at the center of each cluster (three towers per plot) to collect smoke samples for emissions measurements. Each FASS system collected a background sample before the fire was ignited and two canisters from each burn approximately timed to sample separately the flaming and smoldering combustion. The plots were successively burned at approximately 1–2 week intervals throughout the study period. Hoffa et al. [1999] give descriptions of the vegetation fuel types, loads, environmental conditions and fire behavior at these plots. CO$_2$, CO, CH$_4$, and NMHC (C$_2$–C$_3$ aliphatic compounds and some aromatic compounds) were analyzed with gas chromatography (GC) as described by Hao et al. [1996]. The PM$_{2.5}$ concentration was determined from the increase in weight of Teflon filters exposed to the smoke divided by the volume of air sampled [Ward et al., 1996].

The quantification of different compounds emitted from fires is commonly expressed using the emission factor (EF). The EF is the mass of a specific gas or particulate matter emitted by the combustion per unit mass of dry fuel consumed (g kg$^{-1}$). To calculate the EF, the carbon content of the fuel is needed. To make our results comparable with those from previous studies we used a standard carbon fuel (i.e., full conversion to CO$_2$).

To measure the overall variability around the regression lines, the pooled estimate of the variance about the two regression lines, $s^2_{\text{EF-MCE}}$, was computed as

$$s^2_{\text{EF-MCE}} = \frac{\sigma^2_{\text{EF-MCE}_g} + \sigma^2_{\text{EF-MCE}_w}}{n_g + n_w - 4},$$

where $\sigma^2_{\text{EF-MCE}}$ is the standard error of the estimate, and $n_g + n_w - 4 = \nu$ are the degrees of freedom [Glanz, 1997]. Subscripts $g$ and $w$ refer to the grassland and woodland data, respectively. The improvement in the fit obtained by fitting the data sets with separate regression lines, compared to a single regression line was computed using

$$s^2_{\text{EF-MCE}} = \frac{SS_{\text{res}} - SS_{\text{res}}}{2},$$

where $SS_{\text{res}}$ is the sum of squared residuals around the common regression line and $SS_{\text{res}}$ is the sum of squared residuals about the separate regression lines.

The relative improvement in the fit obtained by fitting the two data sets separately was quantified using the $F$ test statistics. This value was then compared with the critical value of the $F$ test statistic for $\nu_g = 2$ numerator
Table 1. Concentrations of Emitted CO$_2$, CO, CH$_4$, NMHC, and PM$_{2.5}$ and the Proportion of Total Fuel Consumed by the Grassland and Woodland Fires

<table>
<thead>
<tr>
<th>Site</th>
<th>CO$_2$, ppm</th>
<th>CO, ppm</th>
<th>CH$_4$, ppm</th>
<th>NMHC, ppm</th>
<th>PM$_{2.5}$, mg m$^{-3}$</th>
<th>FASS Fuel Ratio</th>
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<tr>
<td>G1AF</td>
<td>201.8</td>
<td>19.58</td>
<td>1.061</td>
<td>0.821</td>
<td>1.430</td>
<td>1.00</td>
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<tr>
<td>G1AS</td>
<td>15.8</td>
<td>1.89</td>
<td>0.103</td>
<td>0.120</td>
<td>0.200</td>
<td>0.86</td>
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<td>G1BS</td>
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<td>30.93</td>
<td>1.608</td>
<td>1.311</td>
<td>2.180</td>
<td>0.94</td>
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<tr>
<td>G2AF</td>
<td>93.3</td>
<td>4.87</td>
<td>0.172</td>
<td>0.190</td>
<td>0.350</td>
<td>0.06</td>
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<td>G2AS</td>
<td>198.1</td>
<td>22.33</td>
<td>1.216</td>
<td>1.041</td>
<td>1.620</td>
<td>1.00</td>
</tr>
<tr>
<td>G2BS</td>
<td>3.8</td>
<td>0.61</td>
<td>0.019</td>
<td>0.240</td>
<td>0.000</td>
<td>0.00</td>
</tr>
<tr>
<td>G3AF</td>
<td>246.5</td>
<td>10.55</td>
<td>0.393</td>
<td>0.770</td>
<td>0.990</td>
<td>0.99</td>
</tr>
<tr>
<td>G3AS</td>
<td>1.7</td>
<td>0.10</td>
<td>0.150</td>
<td>0.150</td>
<td>0.010</td>
<td>0.01</td>
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<td>G3BS</td>
<td>233.9</td>
<td>12.15</td>
<td>0.503</td>
<td>0.488</td>
<td>0.645</td>
<td>0.98</td>
</tr>
<tr>
<td>G3CF</td>
<td>7.1</td>
<td>1.19</td>
<td>0.055</td>
<td>0.032</td>
<td>0.290</td>
<td>0.02</td>
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<tr>
<td>G4AF</td>
<td>423.7</td>
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<td>0.569</td>
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<td>0.99</td>
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<td>0.000</td>
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<td>0.787</td>
<td>1.290</td>
<td>1.00</td>
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<td>0.423</td>
<td>0.770</td>
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<tr>
<td>G4DF</td>
<td>198.1</td>
<td>22.33</td>
<td>1.216</td>
<td>1.041</td>
<td>1.620</td>
<td>1.00</td>
</tr>
<tr>
<td>G4DG</td>
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<td>0.61</td>
<td>0.019</td>
<td>0.240</td>
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</tr>
<tr>
<td>G5AF</td>
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<td>0.393</td>
<td>0.770</td>
<td>0.990</td>
<td>0.99</td>
</tr>
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<td>G5AS</td>
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<td>0.10</td>
<td>0.150</td>
<td>0.150</td>
<td>0.010</td>
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<tr>
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<td>12.15</td>
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<td>0.032</td>
<td>0.290</td>
<td>0.02</td>
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<td>0.052</td>
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<td>0.142</td>
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<td>0.381</td>
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<td>0.056</td>
<td>0.056</td>
<td>0.100</td>
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<tr>
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<td>2.55</td>
<td>0.118</td>
<td>0.090</td>
<td>0.080</td>
<td>0.00</td>
</tr>
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</table>
degrees of freedom and \( \nu_d = n_g + n_w - 4 \) denominator degrees of freedom. The \( F \) test statistic is defined as

\[
F = \frac{s_{\text{MCE}}^2}{s_{\text{MCE}}^2}
\]

If the observed value of \( F \) exceeds the critical value of \( F_{\text{crit}} \), it indicates that a significantly better fit to the data (measured by the residual variation about the regression line) was obtained by fitting the two data sets with separate regression lines than by fitting all of the data to a single line.

Finally, we combined all of the EFs from this study with results from the SAFARI-92 and SAFARI-2000 late dry season field campaigns to derive a synthetic regression predictive model for regional EFs from MCEs. The conventional significance level of 95% (\( P < 0.05 \)) was used for all hypotheses tested. Throughout the analyses, checks were performed to test for the assumptions of normality of the residuals and homogeneity of the variances. In some cases, one or both of the assumptions were violated, mostly when all the data were fitted with the common regression line. Other investigators encountered similar problems [e.g., Hoffa et al., 1999; Saarnak, 1999]. Generally, for this region, as the season progresses and the grasses achieve lower moisture content, the combustion process becomes more efficient and the MCE increases.

Hoffa et al. [1999] found that the MCE of the 1996 grassland fires was correlated with the proportion of green grass (PGREEN) in the fuel, with higher moisture content than dead grass. The correlation between MCE and PGREEN is recalculated here since we used a different weighting procedure to derive the grassland MCEs (Figure 3) than Hoffa et al. [1999]:

\[
\text{MCE} = 1.010 - 0.217\text{(PGREEN)}, \quad R^2 = 0.73
\]

It should be pointed out, that despite the different weighting factors used for flaming and smoldering in the 1996 study for the grassland fires compared with Hoffa et al. [1999] the seasonal trends in MCE are similar for both methods of data analysis.

Ward et al. [1996] found, that in woodlands, where grass was a larger fraction of the fuel, the MCE relates to the proportion of the grass in the fuel. In other woodlands, where the grass fuel component is minor, as was the case for the specific 1996 Zambian site (between 7% and 14%), it appears that other fuel types than grass, that increasingly contribute to burning as the dry season progresses, control the MCE. Litter fall occurs as the dry season progresses, so that the amount of leaf litter increases seasonally [Hoffa et al., 1999]. The litter and woody fuels dry slower than the grasses and tend to burn by smoldering, which can lower MCE [Bertschi et al., 2003]. Each fuel type makes a different contribution to the MCE, with litter and woody fuels having the opposite effect compared to the grasses. The combustion factors (the percentage of fuel consumed by the fire) for the burning of all fuel types and the fire intensity generally increase as the dry season progresses [Hoffa et al., 1999]. Whereas though, the grasses tend to involve more flaming combustion which seems to increase the MCE, the litter and woody fuels tend to involve more

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**Table 2.** Early Dry Season Modified Combustion Efficiency and Weighted Average Emission Factors for \( \text{CO}_2 \), \( \text{CO} \), \( \text{CH}_4 \), NMHC, and PM\(_{2.5}\) for Grassland and Woodland Fires

<table>
<thead>
<tr>
<th>Site</th>
<th>Date</th>
<th>MCE</th>
<th>( \text{EFCO}_2 ), g kg(^{-1})</th>
<th>( \text{EFCO} ), g kg(^{-1})</th>
<th>( \text{EFCH}_4 ), g kg(^{-1})</th>
<th>( \text{EFNMHC} ), g kg(^{-1})</th>
<th>( \text{EFPM}_{2.5} ), g kg(^{-1})</th>
</tr>
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<tbody>
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<td>G1</td>
<td>5 June 1996</td>
<td>0.912</td>
<td>1637.4</td>
<td>101.12</td>
<td>3.132</td>
<td>4.734</td>
<td>6.461</td>
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<tr>
<td>G2</td>
<td>14 June 1996</td>
<td>0.913</td>
<td>1638.5</td>
<td>100.35</td>
<td>3.045</td>
<td>5.036</td>
<td>6.293</td>
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<td>G3</td>
<td>26 June 1996</td>
<td>0.955</td>
<td>1735.3</td>
<td>52.27</td>
<td>1.181</td>
<td>2.142</td>
<td>2.842</td>
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<td>9 July 1996</td>
<td>0.963</td>
<td>1754.4</td>
<td>42.98</td>
<td>0.940</td>
<td>1.449</td>
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<td>G5</td>
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<td>0.972</td>
<td>1772.3</td>
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<td>0.584</td>
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<td>0.944</td>
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<td>2.282</td>
<td>2.747</td>
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<td>W4</td>
<td>16 July 1996</td>
<td>0.932</td>
<td>1685.8</td>
<td>78.19</td>
<td>2.529</td>
<td>2.014</td>
<td>5.310</td>
</tr>
<tr>
<td>W5</td>
<td>24 July 1996</td>
<td>0.937</td>
<td>1692.9</td>
<td>72.60</td>
<td>2.185</td>
<td>2.053</td>
<td>6.436</td>
</tr>
<tr>
<td>W6</td>
<td>29 July 1996</td>
<td>0.907</td>
<td>1614.6</td>
<td>105.79</td>
<td>3.921</td>
<td>2.786</td>
<td>15.145</td>
</tr>
</tbody>
</table>

\*MCE, modified combustion efficiency; EF, emission factor.

---

**Note to Table 1**

Italics denote samples that were not included in the analysis on the basis of marginal net concentrations (<20 ppm \( \text{CO}_2 \)). A, B, and C refer to the three sampling clusters centered around each FASS tower that were used to calculate the average at each plot. G, grassland; W, woodland; F, flaming combustion; S, smoldering combustion; I, intermediate combustion.
smoldering combustion and may decrease the MCE. This might explain the lower MCE in the 29 July 1996 woodland burn. Given the vast area and diversity of African woodlands there could be seasonal trends in miombo woodlands, which are not apparent from the limited measurements made in this 1996 study.

3.1.2. Emission Factors

[20] A distinct seasonal trend was observed in the EFs for all measured species in smoke from the dambo grassland fires. The EFCO$_2$ increased as the season progressed due to the higher degree of oxidation from the combustion of the drier fuels, but the variability was small with a maximum difference of about 8.2% (Figure 4a). On the other hand, the EFs of the products of incomplete combustion varied substantially during the fire season (Figures 4b and 5a–5c). On average, they were highest in the first part of the early dry season relative to later in the early dry season by maximum factors of 3.1 for CO, 5.4 for CH$_4$, 4.7 for NMHC and 3.2 for PM$_{2.5}$.

[21] EFs are directly related to PGREEN in grasslands, supporting the hypothesis that as the fuels dry out a higher degree of oxidation is achieved, resulting in more CO$_2$ and less products of incomplete combustion compared with earlier in the dry season when the grasses have a higher moisture content. The regression models of EFs versus PGREEN in grasslands (Figures 6a–6b and 7a–7c) are

\[
\text{EFCO}_2 = 1857.8 - 499.0(P\text{GREEN}), \quad R^2 = 0.76, \quad (2)
\]

\[
\text{EFCO} = -11.06 + 249.02(P\text{GREEN}), \quad R^2 = 0.73, \quad (3)
\]

\[
\text{EFCH}_4 = -0.705 + 8.114(P\text{GREEN}), \quad R^2 = 0.50, \quad (4)
\]

\[
\text{EFNMHC} = -1.631 + 14.298(P\text{GREEN}), \quad R^2 = 0.68, \quad (5)
\]

\[
\text{EFPM}_{2.5} = -0.747 + 16.138(P\text{GREEN}), \quad R^2 = 0.68. \quad (6)
\]

[22] Linking PGREEN to a remotely sensed vegetation condition index, such as the Normalized Difference Vegetation Index (NDVI), which is sensitive to the presence of green vegetation, may be useful for regional applications of the above relationships to estimate emissions from grassland fires.

[23] In the woodland site, the lower EFCO$_2$ (Figure 8a) and the higher EFs for products of incomplete combustion...
combined grassland and woodland data set. A comparison of the $\text{EF}_{\text{CH}_4}$ versus MCE regression models for the woodland and grassland ecosystems (Figure 10a) shows that the mean residual variation for the two separate models is not significantly different from the mean residual variation about a single regression model (i.e., for grassland and woodland EFs taken together) ($F = 1.90 < F_{\text{crit}} = 4.26$). This indicates that for the 1996 data the EFs for CH$_4$ are essentially the same for grassland and woodland savanna fires. No ecosystem difference was found in the $\text{EF}_{\text{CH}_4}$ for controlled burns conducted in different southern African savanna ecosystems during SAFARI-92, as well [Hao et al., 1996].

3.2.2. Nonmethane Hydrocarbons

[25] For NMHC, the mean residual variation about the two ecosystem-specific regression lines is significantly different from that of the common regression line ($F = 36.77 > F_{\text{crit}} = 4.26$), indicating an ecosystem dependence for the $\text{EF}_{\text{NMHC}}$ in the 1996 data (Table 3). Figure 10b illustrates the relationship between EFs and MCE for the two ecosystem types. There is a much greater increase in NMHC emissions with decreasing MCE in grassland than in woodland savannas. At the lowest MCE (0.907) found in this 1996 study, the predicted grassland $\text{EF}_{\text{NMHC}}$ is 86% higher than the measured woodland $\text{EF}_{\text{NMHC}}$ at this MCE.

Thus it appears that using an ecosystem-specific model improves the fit for the 1996 NMHC data. This is in contrast with Hao et al. [1996] who found that the emission ratios of...
NMHC over CH$_4$ were independent of savanna type and fuel amount in the SAFARI-92 measurements.

3.2.3. Particulate Matter

An ecosystem dependence exists also for PM$_{2.5}$ ($F = 6.44 > F_{crit} = 4.46$) (Table 3). There is approximately a difference of a factor of two between the two ecosystems at the lowest MCE in EFPM$_{2.5}$ (Figure 10c). The emissions are higher from woodland savanna than from grassland savanna fires, which is the opposite of what was observed for the NMHC emissions.

The NMHC and PM$_{2.5}$ data indicate that there may be more of an ecosystem dependence early in the dry season than later in the dry season. The ecosystem-specific models for EF versus MCE hinge on a small number of low-MCE samples (especially for woodlands) and they need to be verified by more study. However, if the trends suggested from this unique set of early dry season measurements are valid, this has important implications for estimates of smoke emissions from southern African savanna fires.

3.3. Regional Synthesis of Emission Factors

Figures 11a–11c and Table 3 integrate the EFs from the 1996 study with those from the SAFARI-92 and SAFARI-2000 dry season field campaigns [Ward et al., 1996; Hobbs et al., 2003; Yokelson et al., 2003] to develop regional-average models of EFs versus MCE. Specifically, the woodland and grassland ecosystem-specific regression models from 1996 (Figures 10a–10c) are compared with the regional-average EF models to determine their maximum differences over the corresponding range of MCE values measured in this 1996 study. The regional-average models described in this section are considered to be more robust because they are based on measurements that were conducted in a variety of savanna regions, including humid woodland, semiarid woodland and moist grassland sites, and combine both late and early dry season measurements. In the case of NMHC and PM$_{2.5}$ (Figures 10b–10c and 11b–11c, respectively), the integration of the data sets significantly decreases the regression
coefficients (Table 3). For woodlands, the regional average model predicts an EFNMHC that is 38.9% larger at the lowest MCE of 0.907. The difference decreases with increasing MCE and becomes zero at an MCE value of 0.984. At the mean of all woodland MCE values observed here (0.935) the regional-average approach predicts an EFNMHC that is 32.0% larger compared with the woodland model. On the other hand, the regional-average model predicts an EFNMHC that is lower by 25.1% at the lowest grassland MCE of 0.912 and by 7.2% at the average grassland MCE of 0.945 compared with the grassland model. There is no difference in the grassland EFNMHC when using the two models at the MCE of 0.951 (where the regression lines cross). For MCE values greater than this, the regional average model predicts EFNMHC that are higher than the grassland model. For example, at the highest grassland MCE of 0.972, measured in this 1996 study, the regional average model predicts an EFNMHC that is higher by 77.5% compared with the grassland model.

In the case of EFPM$_{2.5}$, the maximum difference between the regional average and the grassland models of 57.0% occurs at the highest grassland MCE value of 0.972. As the MCE decreases, the difference between the two models decreases but the two models never coincide over the entire range of grassland MCE values measured here. At the lowest grassland MCE of 0.912 the regional-average model predicts an EFPM$_{2.5}$ that is higher by 34.6% compared with the grassland model. Theoretically, the regional-average model will always over predict the grassland MCE values compared with the grassland model, since the calculated concurrence between the two models occurs at an MCE value of greater than 1.000. The regional-average model predicts an EFPM$_{2.5}$ for woodland fires that is higher by 33.6% at the highest woodland MCE value of 0.952, smaller by 31.9% at the lowest woodland MCE value of 0.907, and smaller by 11.7% at the average woodland MCE of 0.935, compared with the woodland model. More measurements are needed in the early dry season to determine if the 1996 data are outliers, or if an ecosystem dependence can be documented more strongly. In the case of CH$_4$ (Figures 10a and 11a), the integration of the data sets produces a small decrease in the correlation coefficient (Table 3) and little difference compared with the ecosystem-specific algorithms.

Table 3. Average Values of Regression Slopes, Intercepts, and Correlation Coefficients for Emission Factors for CO$_2$, CO, CH$_4$, NMHC, and PM$_{2.5}$ Versus the Modified Combustion Efficiency$

\begin{tabular}{|c|c|c|c|c|}
\hline
 & Grasslands & Woodlands & Combined & Regional \\
\hline
\text{EFCO} & & & & \\
\text{Intercept} & $-388.1$ & $-613.6$ & $-436.9$ & $-288.4$ \\
\text{Slope} & $2218.6$ & $2460.7$ & $2270.9$ & $2118.1$ \\
\text{R}^2 & 0.97 & 0.99 & 0.98 & 0.90 \\
\hline
\text{EFCO} & & & & \\
\text{Intercept} & $1145.30$ & $1119.07$ & $1137.23$ & $1158.08$ \\
\text{Slope} & $-1144.79$ & $-1117.02$ & $-1136.34$ & $-1157.63$ \\
\text{R}^2 & 0.99 & 0.99 & 0.99 & 0.98 \\
\hline
\text{EFCH} & & & & \\
\text{Intercept} & $42.951$ & $56.710$ & $47.948$ & $47.737$ \\
\text{Slope} & $-43.630$ & $-58.214$ & $-47.948$ & $-47.737$ \\
\text{R}^2 & 0.94 & 0.98 & 0.94 & 0.81 \\
\hline
\text{EFNMHC} & & & & \\
\text{Intercept} & $65.982$ & $22.757$ & $47.916$ & $36.367$ \\
\text{R}^2 & 0.97 & 0.76 & 0.65 & 0.44 \\
\hline
\text{EFPM$_{2.5}$} & & & & \\
\text{Intercept} & $75.924$ & $211.108$ & $124.050$ & $95.762$ \\
\text{Slope} & $-76.180$ & $-217.932$ & $-126.011$ & $-95.488$ \\
\text{R}^2 & 0.96 & 0.73 & 0.58 & 0.32 \\
\hline
\end{tabular}

$^a$R$^2$, correlation coefficient.

Figure 9. Seasonal emission factors for (a) CH$_4$, (b) NMHC, and (c) PM$_{2.5}$ for woodland fires.
Considering that the data used here were collected in different rainfall years (1992 was dry, 1996 was average, and 2000 was wet), in different locations, and were collected (ground and airborne) and analyzed using different methods (GC and airborne Fourier transform infrared spectroscopy), it is not surprising to find these variations between regional-average and ecosystem-specific EFs. It should be noted, that these differences have different meanings for various users of fire information. For regional and global emissions estimation, the differences in these EFs are likely of lesser importance relative to the larger uncertainties in some of the other modeling variables, such as fuel load and burned area, which may result in emission estimates that vary by an order of magnitude (compare Scholes et al. [1996] with Hao et al. [1990]).

At the same time, it is important to know and consider the differences in EFs discussed here when reporting the overall error of a regional emissions model. For example, Scholes et al. [1996] estimated that their emissions model was accurate to within ±60%. Compared to that level...
of claimed accuracy, the differences between regional-average and ecosystem-specific EFs presented here appear significant and suggest that an ecosystem-specific approach could be more appropriate. The mixture of grassland and woodland fires, which likely changes seasonally and from year to year, will determine the importance of these differences and the resulting implications for regional emissions estimation.

[32] On the other hand, for landscape-level emission studies, for which accurate fuel loading databases are in place (e.g., national parks), EFs might prove to be a larger source of uncertainty than burned area and fuel consumption. Comprehensive ground-based measurements of burned area and fuel consumption are possible at this scale and the availability of high-resolution satellite information (e.g., Landsat, SPOT) permits a reasonably accurate estimation of area burned [e.g., Korontzi et al., 2003]. Field data combined with satellite information can also provide reliable modeling of fuel consumption (T. Landmann, unpublished data, 2000). Unless there are explicit EF measurements over a specific fire event, EFs have to be modeled as shown in the relations for EFCH4 and EFNMHC in Table 4. EF values from [Ward et al., 1996; Hoffa et al., 1999] were used as representative of early dry season EF values. The same EF values were used as representative of early dry season EF values were used as representative of early dry season burning.

[34] Owing to the lack of early dry season data in the literature, Korontzi et al. [2003] and Justice et al. [2002] compared seasonal non-CO2 emissions, using Landsat-derived monthly time series of burned area and calculated seasonal EFs, with emissions using the annual area burned and late dry season values of EFs. It was found that considerable underestimation of products of incomplete combustion occurred when average late dry season EF values were used as representative of early dry season burning.

### Table 4. Comparison of Seasonal Emission Factors for CH4, NMHC, and PM2.5 Predicted From the Combined Grassland-Woodland Models of this 1996 Study With the Corresponding Seasonal Emission Factors Calculated Using the SAFARI-92 Models Over the Range of Modified Combustion Efficiency Values Measured in this Study

<table>
<thead>
<tr>
<th>MCE</th>
<th>% Difference in EFCH4</th>
<th>% Difference in EFNMHC</th>
<th>% Difference in EFP2.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.907</td>
<td>-13.9</td>
<td>1.6</td>
<td>32.6</td>
</tr>
<tr>
<td>0.912</td>
<td>-13.2</td>
<td>1.3</td>
<td>32.0</td>
</tr>
<tr>
<td>0.952</td>
<td>5.5</td>
<td>-2.9</td>
<td>30.0</td>
</tr>
<tr>
<td>0.972</td>
<td>369.0</td>
<td>-10.7</td>
<td>-2.7</td>
</tr>
</tbody>
</table>

[35] As shown above, the seasonality in grassland fire emissions is more apparent compared with woodland fires. To evaluate the potential importance of grassland fire emissions to southern African regional emissions budgets we analyzed the satellite-derived Global Burned Area Product 2000 (GBA-2000) for southern Africa [Silva et al., 2003]. The most recent version of GBA-2000, released in December 2002 (J. M. N. Silva, personal communication, 2003) shows that a total area of approximately 1,071,100 km² burned in southern Africa in 2000, from which about 264,000 km² was in grasslands. The MODIS percent tree cover (PTC) remote sensing product [Hansen et al., 2002] was used to distinguish between ecosystem types. Land areas with PTC less than or equal to 10% were classified as grasslands, whereas areas with PTC greater than 10% and smaller than 80% were classified as woodlands. The threshold PTC value of 10% was derived from the Food and Agricultural Organization of the United Nations (FAO) definition of forest [Food and Agriculture Organization of the United Nations, 2001]. Therefore it appears that at the regional level, grassland fires are important.

[36] Korontzi et al. [2003] demonstrated for grassland fires at the landscape level that due to seasonal effects, burned area is nonlinearly related to emission. The same amount of burned area may produce several times higher emissions of products of incomplete combustion early in the dry season compared with the late dry season. The analysis of GBA-2000 for the main dry season (May—October) in southern Africa shows that 57% of the burning occurs from May to July, 18% in August, 17% in September and 8% in October. The temporal distribution the GBA-2000 is in good general agreement with the TRMM active fire data in Figure 1. These results demonstrate that early dry season burning is widespread, despite the common belief that August and September are the most intensive biomass
burning months in southern Africa, and that temporal patterns of biomass burning need to be integrated in the emissions modeling framework.

3.6. Seasonal Emission Factors for Oxygenated Volatile Organic Compounds

[37] One of the major gaps in our knowledge of the chemistry of the emissions from African savanna fires has been addressed recently by the first quantitative measurements of the EFs for oxygenated volatile organic compounds (OVOC) during the SAFARI-2000 dry season field campaign [Yokelson et al., 2003]. The OVOC are about 5 times more abundant than NMHC in the southern hemisphere and they are more reactive (e.g., acetic acid (CH$_3$COOH), formic acid (HCOOH), and formaldehyde (HCHO), reported here) [Singh et al., 2001]. Methanol (CH$_3$OH), which is fairly long lived, is the second most abundant organic compound in the atmosphere after CH$_4$. Here, we combine our seasonal grassland MCE values and the relationship of MCE versus PGREEN with the relationships of EFOVOC vs. MCE reported by Yokelson et al. [2003] to calculate the first seasonal trends in EF of these compounds for southern African grassland fires (Figure 12) and relate them to PGREEN. In the absence of early dry season EFOVOC versus MCE models, we applied the late dry season relationships to predict the early dry season EFOVOC. The calculated values of the EFOVOC in the early dry season are a maximum of 3.8, 2.4, 3.6, and 2.0 times higher for CH$_3$COOH, HCHO, CH$_3$OH and HCOOH, respectively, than the corresponding values in the late dry season. The OVOC emissions are related to PGREEN as following:

\[
\text{EFCH}_3\text{COOH} = 9.836(\text{PGREEN}) - 0.749, \quad (7)
\]

\[
\text{EFHCHO} = 3.025(\text{PGREEN}) + 0.088, \quad (8)
\]

\[
\text{EFCH}_3\text{OH} = 4.618(\text{PGREEN}) - 0.318, \quad (9)
\]

\[
\text{EFHCOOH} = 1.630(\text{PGREEN}) + 0.188. \quad (10)
\]

Note that the sum of the EFOVOC for the four OVOC that were most abundant in the SAFARI-2000 measurements is greater than the EFNMHC.

4. Conclusions

[38] Savanna fires are believed to produce zero net emissions of CO$_2$ due to its sequestration by subsequent vegetation growth [Scholes et al., 1996]. At the same time
products of incomplete combustion may exhibit significant seasonal variations in their emissions [Hoffa et al., 1999; Justice et al., 2002; Korontzi et al., 2003]. The seasonal budgets of these non-CO$_2$ trace gases and aerosols, and the implications for regional and global atmospheric chemistry, are largely unknown. The contribution of the early dry season emissions to the total annual emissions needs to be quantified.

[39] Information on EFs is required to improve the accuracy of emissions models. We have presented here the first early dry season EF measurements in southern African and they indicate some important and interesting seasonal trends in fire emissions and correlations to fuel characteristics. We have also derived the first seasonal EFOVC for grassland fires and their relation to the proportion of green grass, which due to the importance of OVOC in tropospheric chemistry need to be included in future emissions modeling studies. The results from the integration of the different EF data sets enables estimates of the effects of using regional-average rather than ecosystem-specific EF models. The results presented here indicate that the seasonal trends of fire emissions require further attention. Clearly, a more intensive sampling is required to create a larger database that will allow the development of more robust seasonal EF models as a function of fuel condition. Fires exhibit high variability and the degree to which the seasonal measurements in this paper are representative of African savanna fires should not be overestimated. Through the development of seasonally sensitive emission estimates, it should be possible though, to do a better job of assessing emissions for Intergovernmental Panel on Climate Change (IPCC) national reporting.

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