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Hydrogen peroxide, organic hydroperoxide, and formaldehyde as primary pollutants from biomass burning

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Abstract. Hydrogen peroxide, organic hydroperoxide species, and formaldehyde were found to be enhanced within biomass burning plumes during the Transport and Atmospheric Chemistry near the Equator - Atlantic (TRACE A) experiment. This enhancement could have resulted from direct emission by the fires or by secondary photochemical production. In this study, direct production of hydroperoxide and formaldehyde from biomass burning is proposed and examined through comparisons of hydroperoxide and formaldehyde measurements, obtained from three fire flights in TRACE A, with model estimates, with other measurement data, and with results from fire experiments at the University of Rhode Island (URI). For highest concentrations of hydroperoxide and formaldehyde, model predictions fall short of those observed, and an additional source is required. \( \text{H}_2\text{O}_2 \) and \( \text{CH}_3\text{OOH} \) were noted to increase with CO and were significantly correlated with other measured species known to be produced from biomass burning. The enhancements of \( \text{H}_2\text{O}_2 \) and \( \text{CH}_3\text{OOH} \) relative to CO were different between flights in which the relative enhancements of CO to \( \text{CO}_2 \) were also different. The enhancement ratio of \( \text{H}_2\text{O}_2 \) and \( \text{CH}_3\text{OOH} \) relative to CO was \( 1-5 \times 10^{-2} \) and \( 2-4 \times 10^{-3} \), respectively. \( \text{CH}_2\text{O} \) was correlated with CO. The enhancement ratios of \( \text{CH}_2\text{O} \) were determined in relation to both CO and \( \text{CO}_2 \) for three flights and were \( 7-19 \times 10^{-3} \) and \( 3-5 \times 10^{-4} \), respectively. The correlations of \( \text{CH}_2\text{O} \) with other measured combustion species were more significant than those of \( \text{H}_2\text{O}_2 \) and \( \text{CH}_3\text{OOH} \). To determine whether hydroperoxide and formaldehyde can be directly produced from biomass burning, simple biomass fire experiments were performed at URI. These species were observed to be clearly elevated in test biomass fires. These experiments present unequivocal evidence for the direct production of hydrogen peroxide and formaldehyde from biomass burning. The results from both TRACE A and our fire experiments also fit possible mechanisms of direct formation of hydroperoxide and formaldehyde in combustion processes. The atmospheric implication of the direct production of these species from biomass burning is their contribution to odd-hydrogen radical production, thereby affecting the oxidizing capacity of the atmosphere before \( \text{O}_3 \) would be photochemically developed. In TRACE A, odd-hydrogen radical production from the direct source of these species is estimated to be near 30% of the total radical production.

1. Introduction

Biomass burning is recognized as one of the most important biogeochemical processes with significant impacts on the atmosphere. During biomass burning, a wide range of trace gases including \( \text{CO}_2 \), CO, \( \text{CH}_4 \), NMHC, \( \text{NO}_x \), and \( \text{N}_2\text{O} \) are released into the atmosphere [Cruzén and Andreae, 1990; Andreae, 1993]. \( \text{CO}_2 \), \( \text{N}_2\text{O} \), and \( \text{CH}_4 \) are known greenhouse gases contributing to climate change [Mitchell, 1989]. Halogen gases such as \( \text{CH}_3\text{Cl} \) and \( \text{CH}_2\text{Br} \) produced by biomass burning may have influence on stratospheric ozone chemistry [Mano and Andreae, 1994; Cicerone, 1994]. Photochemical reactions between emitted hydrocarbons and \( \text{NO}_x \) lead to net ozone production. Ozone produces OH in humid air, and CO and \( \text{CH}_4 \) consume OH in the remote atmosphere; therefore biomass burning can affect OH concentrations, atmospheric oxidant concentrations, and the rate of oxidation of reduced compounds [Rodriguez et al., 1991]. Hence biomass burning is believed to play an important role in global change [Levine, 1991; International Council of Scientific Unions (ICSU), 1994].

During the Transport and Atmospheric Chemistry near the Equator - Atlantic (TRACE A) experiment [e.g., Fishman et al., 1994], hydrogen peroxide (\( \text{H}_2\text{O}_2 \)), organic hydroperoxides (i.e., \( \text{CH}_3\text{OOH}, \text{HOCH}_2\text{OOH}, \text{CH}_3\text{CH(OH)}\text{OOH}, \) and \( \text{CH}_3\text{C(O)}\text{OOH} \)) and formaldehyde (\( \text{CH}_2\text{O} \)) concentrations were extremely high in and near biomass burning plumes [Lee et al., 1996]. In the Pacific Exploratory Mission - West, Phase A (PEM-West A) experiment, the highest concentrations of \( \text{H}_2\text{O}_2 \) and \( \text{CH}_3\text{OOH} \) were observed over the Celebes Sea in air believed to be impacted
by fire emissions [Heikes et al., 1996a]. Further, the highest H$_2$O$_2$ and CH$_2$O concentrations measured in the Mauna Loa Observatory Photochemistry Experiment (MLOPEX) were thought to be associated with fire emissions [Heikes, 1992]. These results led us to consider biomass burning as a direct source of H$_2$O$_2$, organic hydroperoxide, and CH$_2$O.

Hydrogen peroxide and methyl hydroperoxide are normally thought of as secondary photochemical products acting as reservoirs of odd-hydrogen radicals (e.g., OH, HO$_2$, and CH$_3$OO). Together with formaldehyde, which is a source of odd-hydrogen radicals, they are also precursors of odd-oxygen (e.g., O$_3$, O, and NO$_2$) [Logan et al., 1981; Kleinman, 1986, 1991]. Both odd-hydrogen and odd-oxygen families are important oxidizing species that determine the distribution and abundance of reactive trace gases in the atmosphere and vice versa [National Academy of Sciences (NAS), 1984]. If H$_2$O$_2$, organic hydroperoxide, and CH$_2$O are directly produced from biomass burning, then their photolysis would enhance radical production near the fire and would affect the oxidizing capacity of the atmosphere [Thompson, 1992]. The TRACE A measurements indicate the potential for the direct production from biomass burning and the need to investigate the degree and extent to which biomass fires affect H$_2$O$_2$, organic hydroperoxide, and formaldehyde and consequently may affect atmospheric oxidants. In this paper we hypothesize the direct production of hydroperoxide and formaldehyde from biomass burning and test this hypothesis with data obtained from three fire flights during TRACE A (flights 6 and 7 over Brazil and flight 10 over Africa) and a limited number of test biomass burns performed at the University of Rhode Island (URI) Bay campus.

2. Observed Hydroperoxide and Formaldehyde in TRACE A

We measured H$_2$O$_2$ and organic hydroperoxide species with high-performance liquid chromatography (HPLC) system mounted in the NASA DC-8 aircraft during TRACE A. The details about the measurement scheme are supplied by Lee et al. [1995]. Formaldehyde was measured during TRACE A by the method of Lazarus et al. [1988] as implemented by Heikes [1992] and Heikes et al. [1996b]. TRACE A was conducted in September-October 1992. Its primary objective was to investigate the cause of a seasonal tropospheric ozone maximum over the South Atlantic observed when biomass burning is the most prevalent in South America and Africa [Fishman, 1994; Fishman et al., 1996]. A comprehensive set of chemical and meteorological data was obtained during 17 flights over the South Atlantic, Brazil, and southern Africa, including several flights within and downwind of fire plumes [Fishman et al., 1996].

Three of 17 flights were made specifically to collect air samples over the biomass burning source regions. H$_2$O$_2$, CH$_2$OOH, and CH$_2$O concentrations were elevated in and near burning plumes and observed up to 10 ppbv, 2 ppbv, and 5 ppbv, respectively. These are extremely high values for H$_2$O$_2$ compared with those from undisturbed background conditions and from theoretical model values, although the CH$_2$O levels are comparable to those observed in urban environments. CH$_2$OOH was only slightly enhanced in the plumes, and other organic hydroperoxides such as hydroxymethyl hydroperoxide (HOCH$_2$OOH: HMHP) and 1-hydroxyethyl hydroperoxide (CH$_3$CH(OH)OOH; 1-HEHP) were sporadically detected during flights 6 and 10. Additional results related to H$_2$O$_2$, CH$_2$OOH, and CH$_2$O from this experiment can be found elsewhere [e.g., Jacob et al., 1996; Heikes et al., 1996c; Lee et al., 1996].

3. Test of Hypothesis

3.1. Comparison of Observed Data With Photochemical Model Result

Figure 1 shows the observed concentrations of H$_2$O$_2$, CH$_2$OOH, and CH$_2$O versus their model values for the three flights near fires: flights 6, 7, and 10. A merged data set indexed

![Figure 1](image-url)
to hydroperoxide data [Jacob et al., 1996] was used in this analysis. The lines indicate a one-to-one ratio between observed and predicted values. Below 5000 pptv of \( \text{H}_2\text{O}_2 \) and 1000 pptv of \( \text{CH}_3\text{OOH} \) these species appear to be near photochemical equilibrium. Above these observed concentrations, however, model values remain nearly constant, leading to greater differences between the two results at higher concentrations. This finding implies that photochemical production is insufficient to support the observed high concentrations of \( \text{H}_2\text{O}_2 \) and an additional source is needed. Although the case for \( \text{CH}_3\text{OOH} \) is visually weaker, Figure 1b suggests \( \text{CH}_3\text{OOH} \) may also require an additional source above 1000 pptv. The higher concentrations of \( \text{H}_2\text{O} \) above 2000 pptv are not displayed in Figure 1c because of the lack of overlap between model and observed data due to the absence of other key chemical parameters needed by the model. However, there is a tendency for theoretical values to fall short of those observed, and an additional source would be necessary.

The observed hydroperoxide and formaldehyde data can be compared with those calculated from a photochemical point model. In general, agreement between observed and predicted results lies within the uncertainties of the measurement and the model calculation [Davis et al., 1996; Jacob et al., 1996]. However, a divergence between model and measurements was noted when high concentrations were observed immediately over biomass burning regions with observed values substantially higher than those predicted. Low model values suggest either missing sources or an overestimate of the sink for these species in fire plumes. An overestimate does not seem plausible, since the deposition of both hydroperoxide and formaldehyde, which is an important removal process for these species, was not included in the model. Further, reduction of OH and photolysis, the primary photochemical sinks for these species, also reduces their production with the resulting concentrations of \( \text{H}_2\text{O}_2 \), \( \text{CH}_3\text{OOH} \), and \( \text{CH}_2\text{O} \) being little changed. Consequently, additional sources are needed to resolve the deviations between model and observed data over biomass fire source regions.

Direct production in biomass fires could cause the increased concentrations of these species in and near plumes. This possibility was not considered in the model. However, there may be short-lived hydrocarbons produced from biomass fires which were not measured during the experiment and which would have been oxidized prior to sampling of the plume by the aircraft. Peroxides might have been enhanced by photochemical reactions involving these hydrocarbons. This theory was also not taken into account in the model. Thus we could not exclusively rule out secondary photochemical production as an additional source for these species.

3.2. Correlation of Hydroperoxide and Formaldehyde With Other Measured Species

\( \text{CO} \) and \( \text{CO}_2 \) are often used to characterize biomass fires and to estimate the emissions of other species [Levine et al., 1991; Lobert et al., 1991]. If \( \text{H}_2\text{O}_2 \), \( \text{CH}_3\text{OOH} \), and \( \text{CH}_2\text{O} \) are directly produced, then they should be significantly correlated with them. The emission of a species \( X \) can be related to the emission of \( \text{CO}_2 \) through an emission ratio, \( ER \), defined by

\[
ER(\text{X}) = \frac{\Delta X}{\Delta \text{CO}_2}
\]

where \( \Delta X \) is the excess concentration of species \( X \) produced by biomass burning over background and \( \Delta \text{CO}_2 \) is the excess concentration of \( \text{CO}_2 \) produced by biomass burning over background. Since the emissions of gases are dependent on the stage of burning (flaming or smoldering), \( \text{CO} \) is also used as a reference gas in calculating emission ratios, \( ER = \Delta X/\Delta \text{CO} \) [Lobert et al., 1991]. There are no data for the direct emission of hydroperoxides from biomass burning. For \( \text{CH}_2\text{O} \), Griffith et al. [1991] made measurements in several prescribed fires and calculated the emission ratio of \( \text{CH}_2\text{O} \) relative to \( \text{CO}_2 \). From ambient measurements of hydroperoxide, formaldehyde, \( \text{CO} \), and \( \text{CO}_2 \) in \( \text{TRACE} \) A, emission ratio could not be determined, because measurements were not confined to fire plumes. In this study the enhancement ratio derived from the slope of the linear regression between the target species and either \( \text{CO} \) or \( \text{CO}_2 \) was
CO can be confounded by H2O, because much of H2O variance with increasing CO concentration. Interpretation of H2O2 versus be seen that the concentrations of H2O2 and CH3OOH increase from the three flights are plotted versus CO in Figure 3. It can of CO 2 is weaker in relation to its background level.

Table 1. Summary of Linear Regression

<table>
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<tr>
<th>Figure</th>
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<th>$p$</th>
<th>N</th>
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Flight 6

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Flight 7

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Flight 10

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</table>

HCOOH, CH3COOH, and HNO3. These species are all indicators of biomass burning [Crutzen and Andreae, 1990; Radke et al., 1991; Helas et al., 1992; Andreae, 1993]. Because of indicated fire variability, all correlations between measured species were made separately for each flight. CO was used as the combustion reference for the enhancement ratios of hydroperoxide and formaldehyde, because the enhancement signal of CO from biomass burning is stronger in relation to its background concentrations, whereas that of CO2 is weaker in relation to its background level.

3.2.1. Hydroperoxide. H2O2 and CH3OOH concentrations from the three flights are plotted versus CO in Figure 3. It can be seen that the concentrations of H2O2 and CH3OOH increase with increasing CO concentration. Interpretation of H2O2 versus CO can be confounded by H2O, because much of H2O variance has been explained in terms of H2O [Luria et al., 1989; Tremmel et al., 1993]. These two hydroperoxides are also significantly correlated within the subset of fire data for each flight (Figure 4).

Table 1 lists the H2O2 and CH3OOH enhancement ratio for each flight. The H2O2 to CO enhancement ratio was $1.5*10^{-3}$, and that for CH3OOH was $2.4*10^{-3}$. Both H2O2 and CH3OOH are highly enhanced relative to CO in flight 7 compared to the other two flights, and the relative enhancement of H2O2 to CH3OOH ($\Delta$H2O2/$\Delta$CH3OOH) is also the highest in flight 7, about twice that of flight 6 or 10 (Table 1). Also, it should be noted that organic hydroperoxides such as HMHP and 1-HEHP were detected in plumes from flights 6 and 10 but not in flight 7. From these observations the production of hydroperoxide appears to be subject to fire conditions.

The different enhancement ratios of CO to CO2 could be a clue for different enhancements of hydroperoxides between flights. This ratio is a proxy for fire temperature with a low ratio indicating high temperature [Lobert et al., 1991]. This ratio is lowest in flight 7, so the fire plumes in flight 7 should be hottest. Because the enhancement of CO is greatest in flight 10 and because the concentrations of aerosol and CH3COOH, which are known to be produced from smoldering fires [Andreae, 1993], also increased with those of CO (not shown), flight 10 has the most consistent smoldering fire signature of the three flights. It is likely that the production of H2O2 is more favorable than that of organic hydroperoxide at high temperature, as discussed below.

H2O2 and CH3OOH are correlated with CH3Cl, aerosol, C2H2, HCOOH, CH3COOH, and HNO3. These species are all indicators of biomass burning [Crutzen and Andreae, 1990; Radke et al., 1991; Helas et al., 1992; Andreae, 1993].

3.2.2. CH2O. Figure 3 and Table 1 show CH2O to be correlated with CO. CH2O concentrations linearly increase with CO concentrations, and the correlation coefficients approach the significance level of those found between CO and CO2. The CH2O to CO enhancement ratio ranged from $7*10^{-3}$ to $19*10^{-3}$ and is the greatest for flight 7.

Griffith et al. [1991] determined the emission ratio of CH2O relative to CO2 in four biomass fires. Their values were 1.9-2.3$*10^{-2}$ and remained constant during the course of the fires.
For comparison, $\Delta CH_2O/\Delta CO_2$ was also calculated for each flight. These values were 3.1-4.7x10^{-4} (Table 1 and Figure 5), lower than those of Griffith et al. [1991]. Our CO enhancement ratios to CO (1.4-6.7x10^{-2}) were also lower than those of Griffith et al. [1991] (0.14-0.2). The correlation of CH$_2$O with other species such as CH$_3$Cl and aerosol were more significant than those for H$_2$O$_2$ and CH$_3$OOH.

This analysis provided convincing evidence for the direct production of CH$_2$O from fires. For hydroperoxide, however, secondary photochemical production through short-lived hydrocarbons seems to remain as a possible alternative to direct production.

3.3. Fire Experiment

To determine whether hydrogen peroxide, organic hydroperoxide species, and formaldehyde are directly produced from biomass burning, three sets of simple burning experiments were performed at the URI Bay campus in the summer of 1995. The emissions from 13 fires using charcoal, straw, or wood as fuel were sampled for H$_2$O$_2$, organic hydroperoxide, and CH$_2$O. The methods employed were the same as those used in TRACE A. The results are shown in Table 2. Direct CH$_2$O production by fire was always observed. H$_2$O$_2$ production observed during the fires was more variable than CH$_2$O production. CH$_3$OOH
showed the least and most various production by fires. High concentrations of organic hydroperoxides such as hydroxymethyl hydroperoxide, ethyl hydroperoxide, peroxyacetic acid, and 1-hydroxyethyl hydroperoxide were sporadically observed during burning. The maximum concentrations of CH$_2$O, H$_2$O$_2$, and organic hydroperoxide species were not observed simultaneously in time during the course of a fire. Qualitatively, the CH$_2$O maximum was >10 times that of H$_2$O$_2$ and >50 times that of CH$_3$OOH. H$_2$O$_2$ maximum was >5 times that of CH$_3$OOH. The results of the charcoal, straw, and wood fires clearly demonstrate the direct production of H$_2$O$_2$, organic hydroperoxides, and CH$_2$O from biomass burning. A CO instrument problem precluded our calculation of emission ratios, and these must be left for future experiments. Extreme care must be exercised in such experiments to prevent condensation in the sample lines from the production of water by fire.


In combustion processes, hydroperoxides can be produced by the following reactions [Barnard and Bradley, 1984; Gardiner, 1984; Hucknall, 1985; Lewis and von Elbe, 1987]:

(R1) $RH + O_2 \rightarrow R + HO_2$
(R2) $RH \rightarrow R + H$
(R3) $R + O_2 \rightarrow RO_2$
(R4) $R + O_2 \rightarrow \text{Alkene} + HO_2$

Figure 3. (continued)

Figure 4. Linear regression between H$_2$O$_2$ and CH$_3$OOH for each flight.
where RH is alkane, R is alky radical, RO is alkoxy radical, and RO₂ is alkyl peroxy radical. These are examples which only include simple alkane chemistry. At high temperatures over 200°C, the backward reaction of (R3) is more favorable than the forward reaction. The organic hydroperoxide formed through (R9) and (R10) is also more prone to thermal decomposition through (R11) at high temperature. Therefore organic hydroperoxides can be an important intermediate only at lower temperature (T < 200°C). As temperature increases, (R4) is more important than (R3), producing RO₂ radicals and leading to the formation of H₂O₂ by (R5) and (R6). The decomposition of H₂O₂ by (R8) occurs at temperatures above 400°C. At temperatures higher than 500°C, CH₂O can react with H₂O and produce H₂O₂. Therefore H₂O₂ has a greater probability for formation and a lower probability for decomposition than organic hydroperoxides at higher temperatures. Consequently, more H₂O₂ than CH₃OOH would be expected in high-temperature fires. The observed trend of hydroperoxide enhancement in TRACE A and our fire experiments fits this expectation.

There are multiple paths leading to CH₂O formation during combustion processes (e.g., (R12) and (R13)), and CH₂O formation occurs over a wide range of fire temperature [Barnard and Bradley, 1984; Gardiner, 1984; Hucknell, 1985; Lewis and von Elbe, 1987]. Hence CH₂O is apt to be formed with less dependence on fire quality than hydroperoxides. This finding is consistent with observed data from both TRACE A and our fire experiments.

5. Atmospheric Implication

Hydroperoxides are reservoirs of odd-hydrogen radicals by their formation and subsequent photolysis. Their removal by wet and dry deposition and reaction with OH is a significant radical sink in the troposphere [Logan et al., 1981; Kleinman, 1986]. If these species are produced directly through processes other than photochemical reactions, however, they can contribute as a direct source of radicals. This study presents evidence for a direct source of hydroperoxide and formaldehyde from biomass burning. The production of odd-hydrogen radicals from the direct source of these species can be estimated from the enhancement ratios relative to CO, CO enhancements, and photolysis rates of H₂O₂, CH₃OOH, and CH₂O. For three fire flights, approximately 30% of the total odd-hydrogen radical production in the lower troposphere near fires may be due to their direct emission.

Since odd-hydrogen radicals are indispensable to make new odd-oxygen radicals, the direct production of these species can affect ozone and the odd-oxygen cycle. The effect of enhanced hydroperoxide and formaldehyde due to biomass burning in TRACE A is to increase odd-hydrogen and odd-oxygen radicals and thus increase the oxidation capacity of the atmosphere [Lee et al., 1996]. The extent and mechanism of their direct production need to be critically determined through additional laboratory experiments before the global consequence of biomass burning can be evaluated.

6. Conclusion

In TRACE A, hydroperoxide and formaldehyde were highly elevated in and near biomass fires. These high concentrations were not explained by photochemical production alone and suggested that an additional source was required. This tendency is clear for H₂O₂ and relatively less clear for both CH₃OOH and CH₂O. The correlations of CH₂O with CO are excellent, providing strong evidence for the direct production of CH₂O from biomass burning. H₂O₂ and CH₃OOH are moderately correlated with CO. The enhancement ratio relative to CO was 1.5x10⁻³, 2-4x10⁻³, and 7-17x10⁻³ for H₂O₂, CH₃OOH, and CH₂O, respectively. From simple fire experiments using charcoal, straw, and wood as fuel, these species were observed to be highly enhanced in comparison with ambient levels. These experiments support
Table 2. Fire Experiments at the University of Rhode Island Bay Campus

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Number of Experiments</th>
<th>CH₂O Number of Fires</th>
<th>Maximum Concentration ppbv</th>
<th>H₂O₂ Number of Fires</th>
<th>Maximum Concentration ppbv</th>
<th>CH₃OH Number of Fires</th>
<th>Maximum Concentration ppbv</th>
<th>Other ROOH a</th>
<th>Observed Species During Fires</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charcoal</td>
<td>7</td>
<td>6</td>
<td>600</td>
<td>4</td>
<td>50</td>
<td>4</td>
<td>11</td>
<td>HMHP, EHP</td>
<td>U</td>
</tr>
<tr>
<td>Straw</td>
<td>2</td>
<td>2</td>
<td>700</td>
<td>2</td>
<td>32</td>
<td>2</td>
<td>6.3</td>
<td>PAA, 1-HEHP</td>
<td>U</td>
</tr>
<tr>
<td>Wood</td>
<td>4</td>
<td>4</td>
<td>650</td>
<td>2</td>
<td>55</td>
<td>3</td>
<td>2.4</td>
<td>PAA, EHP, 1-HEHP</td>
<td>U</td>
</tr>
</tbody>
</table>

Experiments were performed at the University of Rhode Island Bay Campus in July-August 1995.

a HMHP, hydroxymethyl hydroperoxide; EHP, ethyl hydroperoxide; PAA, peroxyacetic acid; 1-HEHP, 1-hydroxyethyl hydroperoxide; and U, unidentified peroxide.
b Number of fire experiments in which elevated concentrations (at least 3 times higher than ambient levels) of each species were observed.
c Maximum concentrations observed during fires.

d the hypothesis that hydroperoxide and formaldehyde are directly produced from biomass fires. The data obtained from TRACE A and fire experiments also comply with possible mechanisms for direct production of hydroperoxide and formaldehyde during combustion processes. In TRACE A, the photolysis of these species produced from fires accounted for about 30% of the total radical production, which is to be a direct source of odd-hydrogen radicals in the troposphere. Thus further study needs to be carried out to determine the mechanism of production and emission factors of these species.

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