Convective injection and photochemical decay of peroxides in the tropical upper troposphere: Methyl iodide as a tracer of marine convection

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Convective injection and photochemical decay of peroxides in the tropical upper troposphere: Methyl iodide as a tracer of marine convection

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ABSTRACT

The convective injection and subsequent fate of the peroxides H$_2$O$_2$ and CH$_3$OOH in the upper troposphere is investigated using aircraft observations from the NASA Pacific Exploratory Mission - Tropics (A) (PEM-Tropics (A)) over the South Pacific up to 12-km altitude. Fresh convective outflow is identified by high CH$_3$I concentrations; CH$_3$I is an excellent tracer of marine convection because of its relatively uniform marine boundary layer concentration, relatively well-defined atmospheric lifetime against photolysis, and high sensitivity of measurement. We find that mixing ratios of CH$_3$OOH in convective outflow at 8-12 km altitude are enhanced on average by a factor of 6 relative to background, while mixing ratios of H$_2$O$_2$ are enhanced by less than a factor of 2. The scavenging efficiency of H$_2$O$_2$ in the precipitation associated with deep convection is estimated to be 55-70%. Scavenging of CH$_3$OOH is negligible. Photolysis of convected peroxides is a major source of the HO$_x$ radical family (OH + peroxy radicals) in convective outflow. The time scale for decay of the convective enhancement of peroxides in the upper troposphere is determined using CH$_3$I as a chemical clock and is interpreted using photochemical model calculations. Decline of CH$_3$OOH takes place on a time scale of a 1-2 days but the resulting HO$_x$ converts to H$_2$O$_2$, so that H$_2$O$_2$ mixing ratios show no decline for ~5 days following a convective event. The perturbation to HO$_x$ at 8-12 km altitude from deep convective injection of peroxides decays on a time scale of 2-3 days for the PEM-Tropics (A) conditions.
1. INTRODUCTION

Updrafts in deep convective clouds can raise boundary layer air into the upper troposphere in a matter of minutes; outflow occurs primarily from the cloud top and anvil [Chatfield and Crutzen, 1984]. Model studies have suggested that convective injection of the peroxides H$_2$O$_2$ and CH$_3$OOH could provide an important source of hydrogen oxide radicals (HO$_x$ = OH + peroxy radicals) to the upper troposphere, resulting in enhanced production of O$_3$ and gas-phase H$_2$SO$_4$ [Chatfield and Crutzen, 1984; Prather and Jacob, 1997]. Jaeglé et al. [1997, 1998] found that recent observations of OH and HO$_2$ in the upper troposphere [Brune et al., 1998; Wennberg et al., 1998] are consistent with a major source of HO$_x$ from convective injection of peroxides and formaldehyde. In the present study we use aircraft observations of CH$_3$I, H$_2$O$_2$ and CH$_3$OOH taken up to 12-km altitude over the tropical South Pacific to investigate the convective injection and subsequent chemical decay of peroxides in the upper troposphere. As previously shown by Davis et al. [1996] and further demonstrated here, CH$_3$I provides a sensitive tracer of deep marine convection.

The peroxides H$_2$O$_2$ and CH$_3$OOH are produced in the atmosphere by combination reactions of the HO$_x$ radicals, HO$_2$ + HO$_2$ and CH$_3$O$_2$ + HO$_2$ respectively. They photolyze on a time scale of the order of one day to regenerate HO$_x$ radicals, and thus serve as reservoirs for HO$_x$. Water vapor is the main source of HO$_x$ in most of the troposphere, so that the abundance of peroxides is correlated in general with humidity. Mixing ratios of H$_2$O$_2$ and CH$_3$OOH are of the order of 1000 pptv in the marine boundary layer and 100pptv in the upper troposphere [Heikes et al., 1996]. The large concentration gradient between the boundary layer and the upper troposphere, combined with the 10-day characteristic time for
overturning of the upper troposphere with boundary layer air in the tropics [Prather and Jacob, 1997], implies that deep marine convection could provide a major source of peroxides to the upper troposphere. On the basis of the respective Henry’s Law constants for H$_2$O$_2$ and CH$_3$OOH, $8 \times 10^4$ M atm$^{-1}$ and $3 \times 10^2$ M atm$^{-1}$ at room temperature [O’Sullivan et al., 1996], one would expect H$_2$O$_2$ but not CH$_3$OOH to be scavenged in the precipitation associated with the convective updraft [Chatfield and Crutzen, 1984]. In the upper troposphere the peroxides photolyze to release HO$_x$, and subsequent cycling takes place within the HO$_y$ family (sum of HO$_x$ and peroxides). Eventual conversion of HO$_y$ back to water vapor terminates the process. A schematic of the resulting life cycle for HO$_y$ is shown in Figure 1.

The observations analyzed in this paper are from the Pacific Exploratory Mission - Tropics (A) (PEM-Tropics (A)) flown in September-October 1996 [Hoell et al., 1998]. PEM-Tropics (A) used two aircraft, a DC-8 and a P-3B, to survey atmospheric composition over a broad expanse of the Pacific from 45$^\circ$N to 72$^\circ$S. Most of the data were collected between 0$^\circ$S and 30$^\circ$S and extended zonally across the South Pacific. We limit our attention to data from the DC-8, which had a higher ceiling (12-km) than the P-3B (7-km). Measurements aboard the DC-8 included H$_2$O$_2$, CH$_3$OOH, CH$_3$I, and a number of other species. We use CH$_3$I together with high relative humidity as a tracer of fresh outflow of marine convection in the upper troposphere (section 2). From there we examine the enhancement of peroxides and other species in the convective outflow and estimate scavenging efficiencies in the precipitation associated with deep convection (section 3). We then use CH$_3$I as a chemical clock to determine the time scale for decay of HO$_y$ in the upper troposphere following convection, and interpret the results with a photochemical model calculation (section 4).
Conclusions are in section 5.

2. METHYL IODIDE AS A TRACER OF MARINE CONVECTION

Methyl iodide (CH$_3$I) is emitted ubiquitously by the oceans. Though biological production of CH$_3$I may be important in coastal and upwelling regions, photochemical reactions of methyl radicals and iodine atoms in seawater are thought to be the dominant marine source [Moore and Zafiriou, 1994; Happell and Wallace, 1996; Manley and de la Cuesta, 1997]. Indeed, in the marine boundary layer during PEM-Tropics (A), concentrations of methyl iodide were not correlated with concentrations of biologically produced marine tracers such as DMS. Biomass burning is thought to be a much smaller source of CH$_3$I emissions globally [Andreae et al., 1996], but as discussed below, its impacts are non-negligible even over the remote Pacific.

Methyl iodide is removed from the atmosphere mainly by photolysis, with a mean lifetime of 4 days in the tropical troposphere (Figure 2). Oxidation by OH accounts for only ~1% of the loss from photolysis. The Henry’s Law constant of CH$_3$I is sufficiently low ($K_H=0.14$ M atm$^{-1}$ at room temperature [Moore et al., 1995]) that rainout is negligible.

Observations in PEM-Tropics (A) indicate relatively uniform concentrations of CH$_3$I in the marine boundary layer (MBL) over the south tropical Pacific, with an interquartile range of 0.21-0.44 pptv at 0-2 km altitude (Figure 3). This is a much narrower range than that observed for other marine tracers such as DMS which have highly variable biological sources [Andreae et al., 1985]. Atmospheric measurements of CH$_3$I concentrations can be made with high sensitivity (detection limit of 0.01 pptv) [D. Blake et al., 1996]. The combination of relatively uniform boundary layer concentration, relatively well-defined lifetime, and low
limit of detection makes CH\textsubscript{3}I an attractive tracer for deep marine convection and the age of air in the upper troposphere. A parallel can be drawn to the radioisotope \textsuperscript{222}Rn, which is emitted by soils and provides a sensitive tracer of continental convection [Jacob et al., 1997].

Figure 4a shows the latitudinal distribution of CH\textsubscript{3}I mixing ratios measured in PEM-Tropics (A). Values are higher in the tropics than at high southern latitudes, as might be expected from the trend in UV radiation and hence in the photochemical source. We focus our analysis on the southern tropics (0\textdegree-30\textdegree S), where mixing ratios are high and relatively uniform and where the aircraft data are most extensive. Mixing ratios of CH\textsubscript{3}I in the tropics decline by a factor of 5 on average from the surface to 4 km altitude and are then relatively uniform up to 12-km altitude (Figure 5a). The lack of vertical gradient above 4 km suggests a major contribution from deep convection to vertical transport. Vertical gradients are least at the western edge of the flight domain near the highly convective Pacific Warm Pool (west of 170\textdegree E). Mixing ratios of CH\textsubscript{3}I over this region decline by only a factor of two in the lower 4 km, in contrast to a factor of 5 over the rest of the Pacific.

Previous aircraft observations of CH\textsubscript{3}I during the same season (September-October) were made in the PEM-West (A) campaign over the western equatorial Pacific [Hoell et al., 1996] and the TRACE-A campaign over biomass burning regions of Brazil and southern Africa [Fishman et al., 1996]. The CH\textsubscript{3}I mixing ratios measured over the Pacific in PEM-West (A) [Davis et al., 1996] and in a shipboard mission [Yokouchi et al., 1997] were about a factor of 2 higher than in PEM-Tropics (A) although the vertical distributions in PEM-West (A) were similar. Even higher CH\textsubscript{3}I mixing ratios, averaging 0.7-0.9 pptv in the boundary layer and 0.2-0.4 pptv at 8-12 km, were measured over Brazil and South Africa during TRACE-A [N.
Blake et al., 1996. These high mixing ratios point to a large biomass burning source of CH$_3$I in addition to the oceanic source.

Biomass burning pollution layers were sampled throughout the South Pacific troposphere during PEM-Tropics (A) [Schultz et al., 1998]. Interference from biomass burning must be considered when using CH$_3$I as a tracer of marine convection. Most measurements of elevated CH$_3$I at 8-12 km altitude (>0.11 pptv, top octile) displayed corroborating signs of recent marine convection: high humidity, high mixing ratios of bromoform, and low O$_3$ mixing ratios (Table 1). However, as shown in Table 1, some of the high-CH$_3$I measurements were associated with low humidity (<10 % with respect to ice) and high C$_2$H$_2$ mixing ratios (80-300 pptv), indicating biomass burning pollution rather than marine convection as the source of CH$_3$I. To distinguish recent marine convection from biomass burning pollution in the PEM-Tropics (A) data at 8-12 km altitude, we used relative humidity as a corroborating tracer of convection (Table 1). All points with both CH$_3$I and relative humidity in the top octile (CH$_3$I>0.11 pptv, relative humidity >50% with respect to ice) also had elevated mixing ratios of bromoform as well as low C$_2$H$_2$, O$_3$, and NO.

3. CONVECTIVE PUMPING AND SCAVENGING OF PEROXIDES

Latitudinal and vertical distributions of the peroxides measured in PEM-Tropics (A) are shown in Figures 4 and 5. The large-scale spatial trends follow the trends in the photochemical source [Logan et al., 1981; O’Sullivan et al., 1998]. Schultz et al. [1998] examined the extent to which the peroxide concentrations measured in PEM-Tropics (A) could be explained from a photochemical steady-state model calculation constrained with the local aircraft observations of chemical, radiative, and meteorological variables. Primary sources of
HO\textsubscript{x} in that calculation included the O(\textsuperscript{1}D) + H\textsubscript{2}O reaction and the photolysis of acetone (for which a constant mixing ratio of 400 pptv was assumed). They found that the steady-state calculation reproduces observed peroxide concentrations to within 35\% on average below 8-km altitude, but underestimates CH\textsubscript{3}OOH by a factor of 2 and H\textsubscript{2}O\textsubscript{2} by 30\% on average at 8-12 km. Convective transport would be a likely explanation for the underestimate of CH\textsubscript{3}OOH at high altitude, although the magnitude of the bias is within the uncertainty of the low-temperature rate constant for the CH\textsubscript{3}O\textsubscript{2} + HO\textsubscript{2} reaction [DeMore et al., 1997].

The role of convection in enhancing CH\textsubscript{3}OOH concentrations in the upper troposphere is evident from Table 1. The mean CH\textsubscript{3}OOH mixing ratio above 8 km is 6 times higher in convective outflow than in background air. The mean H\textsubscript{2}O\textsubscript{2} mixing ratio in convective outflow is also elevated but by less than a factor of 2. The CH\textsubscript{3}OOH/CH\textsubscript{3}I concentration ratio in fresh convective outflow is similar to that in the boundary layer, indicating no significant scavenging of CH\textsubscript{3}OOH in the precipitation associated with deep convection.

We estimate the scavenging efficiency of H\textsubscript{2}O\textsubscript{2} in deep convection by modeling the observed composition of the fresh convective outflow (conv) in Table 1 as a two-component mixture of boundary layer air (BL) and background upper tropospheric air (UT). The fraction \( \beta \) of UT air in this mixture represents a dilution factor for the convected air and is given by:

\[
\beta = \frac{X_{BL} - X_{\text{conv}}}{X_{BL} - X_{\text{UT}}} \tag{1}
\]

where \( X \) is the mixing ratio of an insoluble tracer such as CHBr\textsubscript{3}, CH\textsubscript{3}OOH, or CH\textsubscript{3}I that is conserved during convective transport. Consider a water-soluble species (mixing ratio \( Y \)) scavenged with an efficiency \( \alpha \) during convective transport. Our two-component model gives
\[ Y_{\text{conv}} = (1 - \alpha)(1 - \beta)Y_{BL} + \beta Y_{UT} \]  
(2)

and rearrangement yields an expression for the scavenging efficiency \( \alpha \):

\[ \alpha = 1 - \frac{Y_{\text{conv}} - \beta Y_{UT}}{(1 - \beta)Y_{BL}} \]  
(3)

Scavenging efficiencies for \( \text{H}_2\text{O}_2 \), \( \text{H}_2\text{O} \), and \( \text{SO}_2 \) in deep convection are given in Table 2 using the mean observations in Table 1 and either of the reference tracers \( \text{CHBr}_3 \), \( \text{CH}_3\text{OOH} \), or \( \text{CH}_3\text{I} \) to derive the dilution factor \( \beta \). Changes in \( \alpha \) depending on the reference tracer used give some measure of the uncertainty of the approach. We derive in this manner an \( \text{H}_2\text{O}_2 \) scavenging efficiency of 55-70\%. A higher scavenging efficiency is found for \( \text{SO}_2 \) (65-95\%), presumably reflecting oxidation by \( \text{H}_2\text{O}_2 \) in convective clouds. Water vapor is even more efficiently scavenged (90\%) because of its low vapor pressure at convective outflow temperatures.

4. FATE OF PEROXIDES IN THE UPPER TROPOSPHERE

Once injected in the upper troposphere, the peroxides decay and supply a source of \( \text{HO}_x \) (Figure 1). The time scale for decay of the peroxide enhancement following a convective event can be estimated in the PEM-Tropics (A) data by plotting the peroxide mixing ratios versus the \( \text{CH}_3\text{I} \) mixing ratio taken as a time coordinate (Figure 6). Also shown in Figure 6 are results from a time-dependent, 0-dimensional photochemical model simulation [Schultz et al., 1998] for an air parcel initialized with the fresh convective outflow composition in Table 1. Acetone and \( \text{CH}_2\text{O} \), not measured in PEM-Tropics (A), are initialized with mixing ratios of 400 pptv and 60 pptv respectively [Wang et al., 1998]. The \( \text{NO}_x \) concentration is held constant in the simulation and no dilution of the air parcel with time is allowed. The \( \text{O}_3 \) column is
6.7x10^{18} \text{ molecules cm}^{-2}, \text{ average of tropical observations in PEM-Tropics (A). Circles plotted}
\text{ every 24 hours on the model curves in Figure 6 convert the CH}_3\text{I coordinate to time. The}
trend of peroxide vs. CH}_3\text{I concentrations computed with the model is roughly consistent}
\text{ with the observations although the scatter in the observations is large.}

We see from Figure 6 that observed concentrations of CH}_3\text{OOH decline on a time scale}
of 1-2 days following a convective event. In contrast, observed concentrations of H}_2\text{O}_2\text{ show}
\text{ no significant decline for } \sim 5 \text{ days following convection and then decline to steady state. We}
\text{ explain the longer persistence of H}_2\text{O}_2\text{ as reflecting the cycling within the HO}_y\text{ family (Figure}
1); recycling of peroxides from HO}_x\text{ in the upper troposphere favors H}_2\text{O}_2\text{ over CH}_3\text{OOH}
\text{ because of the dominance of CO over CH}_4\text{ as a sink for OH.}

The dominant sink of HO}_y\text{ in fresh convective outflow in the model is the oxidation of}
CH}_3\text{OOH by OH:}
\[ CH}_3\text{OOH} + OH \rightarrow CH}_3\text{O}_2 + H}_2\text{O } \quad (4)\]

while the dominant sink in background air is the reaction of OH with HO}_2:\n\[ OH + HO}_2 \rightarrow H}_2\text{O} + O}_2 \quad (5)\]

The time scale for relaxation of HO}_y\text{ to steady state following the convective perturbation can}
\text{ be inferred from the trend in the sum of H}_2\text{O}_2\text{ and CH}_3\text{OOH, which account for about 95\% of}
\text{ total HO}_y\text{ in the model. Results in Figure 6 indicate an effective e-folding lifetime of 2-3 days}
\text{ for HO}_y\text{ both in the model and in the observations.}

This e-folding lifetime is longer than the standard lifetime computed in the model from
the ratio of the HO_y concentration to the 24-hour average HO_y loss rate, which varies from 1.3 days in fresh convective outflow to 1.5 days in aged air. The reason is that photolysis of the peroxides in the outflow produces OH, which oxidizes CH_4 to produce CH_2O; photolysis of this CH_2O then regenerates HO_y, thus sustaining the HO_y enhancement in the outflow for longer than would be expected from the standard calculation of HO_y lifetime. The effective e-folding lifetime of the HO_y enhancement for the PEM-Tropics (A) conditions is still much shorter than the 6-day value reported by Jaeglé et al. [1997] in model calculations for the wintertime upper troposphere over Hawaii. Higher sun angles in PEM-Tropics (A) are the principal factor for this difference; lower O_3 columns and higher NO_x concentrations (which facilitate reaction (5) by increasing the OH/HO_2 concentration ratio) also contribute.

We find in our model that HO_x concentrations in convective outflow are 50% higher than in the background upper troposphere (Table 3). About half of this enhancement is due to convected water vapor, and half is due to convected peroxides (we do not account for convective enhancements of acetone or formaldehyde due to lack of observations). Larger relative enhancements of HO_x in convective outflow were found in previous studies [Jaeglé et al., 1997, 1998]. The weaker effect in PEM-Tropics (A) is due to high sun angles, low O_3 columns, and high humidities, which maintained a large rate of primary HO_x production from the O(1D)+H_2O reaction in background air up to the 12-km ceiling of the aircraft. We see from Table 3 that concentrations of OH are not enhanced in the convective outflow, because the added source of HO_x is balanced by the additional OH sink from oxidation of convected CH_3OOH. Concentrations of CH_3O_2 are almost twice as high in convective outflow as in background air due to the source from convected CH_3OOH. Although the role of convective
injection of peroxides in enhancing HO$_x$ concentrations is relatively small for the PEM-Tropics (A) conditions, the general results obtained here regarding the convective injection, scavenging, and decay of peroxides should be applicable to other upper tropospheric regions where the effect on HO$_x$ is more important.

5. SUMMARY AND CONCLUSIONS

We used aircraft observations over the tropical South Pacific up to 12-km altitude to examine the deep convective injection of peroxides to the upper troposphere and the subsequent chemical decay of these peroxides. Convective outflow at 8-12 km was identified by a combination of elevated CH$_3$I and elevated relative humidity. CH$_3$I is an excellent tracer of marine convection in the upper troposphere because of its relatively uniform marine boundary layer concentrations, its relatively well-defined atmospheric lifetime (photolysis is the main sink, with a lifetime of about 4 days in the tropics), and its low detection limit. Interference from biomass burning pollution is a problem but can be screened out using concurrent observations of high relative humidity and C$_2$H$_2$. Though not used extensively in this study, CHBr$_3$ exhibits similar traits to CH$_3$I and could also serve as a tracer of marine convection.

We found that concentrations of CH$_3$OOH in convective outflow at 8-12 km altitude were elevated by a factor of 6 relative to the upper tropospheric background, while concentrations of H$_2$O$_2$ were elevated by less than a factor of 2. Scavenging by precipitation in the convective updraft was negligible for CH$_3$OOH and 55-70% for H$_2$O$_2$. Photolysis of convected peroxides was a major source of HO$_x$ in the convective outflow.
Formaldehyde is an additional HO\textsubscript{x} precursor injected to the upper troposphere by deep convection but no measurements of CH\textsubscript{2}O were made in PEM-Tropics (A). If boundary layer CH\textsubscript{2}O mixing ratios were 600-1000 pptv, as found in some shipboard measurements over the equatorial Pacific [Arlander et al., 1990], then convective pumping of CH\textsubscript{2}O would be of comparable importance to peroxides as a source of HO\textsubscript{x} in convective outflow. However, models and most observations indicate CH\textsubscript{2}O mixing ratios of 100-300 pptv in the tropical marine boundary layer [Jacob et al., 1996]. At these levels, transport of CH\textsubscript{2}O in deep marine convection provides only a minor source of HO\textsubscript{x} in the upper troposphere [Prather and Jacob, 1997; Jaeglé et al., 1997].

We estimated the rate of chemical decay of the peroxides in the upper troposphere following convective injection by using concurrent observations of H\textsubscript{2}O\textsubscript{2}, CH\textsubscript{3}OOH, and CH\textsubscript{3}I concentrations, with CH\textsubscript{3}I serving as a photochemical clock. Results were compared to a photochemical model simulation. Concentrations of CH\textsubscript{3}OOH declined with an e-folding lifetime of 1-2 days due to losses from photolysis and reaction with OH. The HO\textsubscript{x} produced from photolysis of CH\textsubscript{3}OOH was recycled to H\textsubscript{2}O\textsubscript{2}. Concentrations of H\textsubscript{2}O\textsubscript{2} thus did not decline for about 5 days following convective injection. The perturbation to HO\textsubscript{x} from the convective injection of peroxides decayed on a time scale of 2-3 days; this time-scale is relatively short because of the intense radiation over the tropical South Pacific.

Photochemical model results for the PEM-Tropics (A) conditions indicate a 50% enhancement of HO\textsubscript{x} in convective outflow relative to background air at 8-12 km altitude. Half of this enhancement is due to convected water vapor and half is due to convected peroxides. As pointed out by Folkins et al. [1998], convective enhancement of HO\textsubscript{x} in the
upper troposphere by deep marine convection is in general inefficient as a source of O$_3$ because the outflow contains low concentrations of NO$_x$. In continental convection, by contrast, convective injection of peroxides and CH$_2$O leads to rapid O$_3$ production because of the large concurrent source of NO$_x$ from lightning and pumping of continental pollution [Jaegle et al., 1998].

Acknowledgments

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methyl iodide, ethyl iodide, bromoform, and dibromomethane over the ocean (east and southeast Asian seas and the western Pacific).” *J. Geophys. Res.*, 102, 8805-8809, 1997.
Figure captions

figure 1: Schematic of the convective injection of peroxides and the cycling of HOy in the upper troposphere

figure 2: Vertical profiles of the 24-hour average photolysis frequency of CH$_3$I for three different latitudes. Calculations were done for a solar declination angle of 0° (equinox), an ozone column of 280 DU, and cloud-free conditions. Absorption cross-sections for CH$_3$I are taken from Roehl et al. (1997) and a quantum yield of unity for photolysis is assumed.

figure 3: Probability distribution of CH$_3$I concentrations over the tropical South Pacific at 0-2 km altitude (circles) and at 8-12 km altitude (triangles). The abscissa is a normal probability scale that a normal distribution would plot as a straight line with standard deviations indicated as the quantiles of standard normal.

figure 4: Latitudinal distributions of median mixing ratios of (a) CH$_3$I, (b) CH$_3$OOH, and (c) H$_2$O$_2$ at 0-2 km altitude in PEM-Tropics (A). Each symbol contains at least 10 samples.

figure 5: Vertical profiles of mixing ratios of (a) CH$_3$I, (b) CH$_3$OOH, and (c) H$_2$O$_2$ measured in PEM-Tropics (A) at 0°-30°S latitude. Squares represent median values and lines represent interquartile ranges. In (a), darkened circles represent the subset of CH$_3$I mixing ratios over the West Pacific Warm Pool, west of 170°E and north of 15°S, an area of particularly intense convection. Each square contains at least 80 samples, each circle contains at least 5 samples; the interquartile range is not shown if there were less than 10 samples.
figure 6: Mixing ratios of (a) CH$_3$OOH, (b) H$_2$O$_2$, and (c) the sum of peroxides vs. the CH$_3$I mixing ratio measured in PEM-Tropics (A) at 0°-30°S latitude. Plus signs denote individual observations, large crosses are mean values and standard deviations for CH$_3$I octiles. Data with strong biomass burning influence (C$_2$H$_2$ > 80 pptv) were excluded. Open circles are results from a photochemical model calculation (see text); each circle represents an aging time of one day in the model starting from fresh convective outflow.
Table 1: Air mass compositions at 0-2 km and 8-12 km altitude over the tropical South Pacific

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<tr>
<td>HNO₃ (pptv)</td>
<td>36 ± 53</td>
<td>25 ± 15</td>
<td>43 ± 18</td>
<td>100 ± 58</td>
<td>75 ± 59</td>
</tr>
<tr>
<td>Ozone (ppbv)</td>
<td>25 ± 11</td>
<td>27 ± 7</td>
<td>29 ± 8</td>
<td>61 ± 29</td>
<td>51 ± 22</td>
</tr>
<tr>
<td>Water vapor (ppmv)</td>
<td>15100 ± 6500</td>
<td>700 ± 520</td>
<td>160 ± 150</td>
<td>70 ± 70</td>
<td>130 ± 110</td>
</tr>
<tr>
<td>Rel. Humidity b</td>
<td>75% ± 19%</td>
<td>82% ± 14%</td>
<td>21% ± 14%</td>
<td>6% ± 1%</td>
<td>13% ± 12%</td>
</tr>
<tr>
<td>DMS (pptv)</td>
<td>48 ± 54</td>
<td>7 ± 11</td>
<td>2 ± 5</td>
<td>2 ± 2</td>
<td>&lt; 0.8c</td>
</tr>
<tr>
<td>CHBr₃ (pptv)</td>
<td>1.0 ± 0.4</td>
<td>0.76 ± 0.13</td>
<td>0.44 ± 0.18</td>
<td>0.61 ± 0.38</td>
<td>0.33 ± 0.17</td>
</tr>
<tr>
<td>SO₂ (pptv)</td>
<td>31 ± 29</td>
<td>13 ± 6</td>
<td>14 ± 5.5</td>
<td>18 ± 3</td>
<td>18 ± 15</td>
</tr>
<tr>
<td>CO (pptv)</td>
<td>62 ± 13</td>
<td>57 ± 4</td>
<td>61 ± 4</td>
<td>92 ± 31</td>
<td>64 ± 13</td>
</tr>
<tr>
<td>C₂H₂ (pptv)</td>
<td>44 ± 33</td>
<td>33 ± 10</td>
<td>37 ± 10</td>
<td>130 ± 90</td>
<td>57 ± 34</td>
</tr>
</tbody>
</table>

Means and standard deviations of concentrations measured at 0°-30°S latitude during PEM-Tropics (A). The following selection criteria were applied: Recent marine convection: CH₃I and relative humidity both in the top octiles of measurements at 8-12 km altitude (i.e., CH₃I > 0.11pptv, relative humidity > 50%). All cases meeting these criteria also had low biomass burning influence (C₂H₂ < 80pptv). Aged convective outflow: CH₃I > 0.11 pptv, relative humidity < 50%, and C₂H₂ < 80 pptv. Biomass burning pollution: CH₃I > 0.11 pptv, relative humidity < 50%, and C₂H₂ > 80pptv. The rest of the data (i.e. CH₃I < 0.11 pptv and relative humidity < 50%) were labeled background conditions.

a NOₓ = NO + NO₂; NO₂ is calculated with a photochemical steady state model [Schultz et al., 1998].

b Relative humidity is defined with respect to ice.

c Detection limit for the DMS measurements.
Table 2: Scavenging efficiencies of gases during deep convection

<table>
<thead>
<tr>
<th>Reference Tracer</th>
<th>CHBr₃</th>
<th>CH₃OOH</th>
<th>CH₃I</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dilution factor β</td>
<td>0.36</td>
<td>0.58</td>
<td>0.68</td>
</tr>
<tr>
<td>Scavenging efficiency α</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H₂O₂</td>
<td>70%</td>
<td>62%</td>
<td>55%</td>
</tr>
<tr>
<td>Water Vapor</td>
<td>93%</td>
<td>90%</td>
<td>87%</td>
</tr>
<tr>
<td>SO₂</td>
<td>67%</td>
<td>80%</td>
<td>94%</td>
</tr>
</tbody>
</table>

The scavenging efficiency α is defined as the fraction of species scavenged by precipitation in air convected from the marine boundary layer to 8-12 km altitude. Values are calculated from equation (3) using the mean air mass compositions from Table 1 and either of the reference tracers CHBr₃, CH₃OOH, or CH₃I to derive the dilution factor β by equation (1).
Table 3: Sources and sinks of HO$_x$ at 8-12 km altitude

<table>
<thead>
<tr>
<th>HO$_x$ concentrations, $10^7$ molecules cm$^{-3}$</th>
<th>fresh convective outflow</th>
<th>background</th>
</tr>
</thead>
<tbody>
<tr>
<td>total HO$_x$</td>
<td>7.4</td>
<td>5.0</td>
</tr>
<tr>
<td>HO$_2$</td>
<td>5.2</td>
<td>3.7</td>
</tr>
<tr>
<td>CH$_3$O$_2$</td>
<td>2.1</td>
<td>1.2</td>
</tr>
<tr>
<td>OH</td>
<td>0.11</td>
<td>0.11</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>HO$_x$ sources, $10^4$ molecules cm$^{-3}$ s$^{-1}$</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>O($^1$D)+H$_2$O</td>
<td>4.9</td>
<td>2.1</td>
</tr>
<tr>
<td>H$_2$O$_2$ + hv</td>
<td>3.1</td>
<td>1.7</td>
</tr>
<tr>
<td>CH$_2$O + hv</td>
<td>2.9</td>
<td>2.3</td>
</tr>
<tr>
<td>CH$_3$OOH + hv</td>
<td>2.5</td>
<td>0.9</td>
</tr>
<tr>
<td>Acetone + hv</td>
<td>0.5</td>
<td>0.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>HO$_x$ sinks, $10^4$ molecules cm$^{-3}$ s$^{-1}$</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>HO$_2$ + HO$_2$</td>
<td>5.1</td>
<td>2.3</td>
</tr>
<tr>
<td>HO$_2$ + CH$_3$O$_2$</td>
<td>4.4</td>
<td>1.5</td>
</tr>
<tr>
<td>OH + HO$_2$</td>
<td>3.4</td>
<td>2.5</td>
</tr>
<tr>
<td>other</td>
<td>1.0</td>
<td>1.2</td>
</tr>
</tbody>
</table>

24-hour mean concentrations, sources and sinks of HO$_x$ obtained in a photochemical model [Schultz et al., 1998] constrained with the mean observations for fresh convective outflow and background upper tropospheric air over the tropical South Pacific in PEM-Tropics (A) (Table 1).
Figure 1.
figure 2
Figure 3
Figure 4

a) \( \text{CH}_3\text{I} \)

b) \( \text{CH}_3\text{OOH} \)

c) \( \text{H}_2\text{O}_2 \)
Figure 5

(a) CH₃I

(b) CH₃OOH

(c) H₂O₂
figure 6