

# Global and regional effects of the photochemistry of $\text{CH}_3\text{O}_2\text{NO}_2$ : evidence from ARCTAS

E. C. Browne<sup>1</sup>, A. E. Perring<sup>1,\*\*\*</sup>, P. J. Wooldridge<sup>1</sup>, E. Apel<sup>2</sup>, S. R. Hall<sup>2</sup>, L. G. Huey<sup>3</sup>, J. Mao<sup>4</sup>, K. M. Spencer<sup>5</sup>, J. M. St. Clair<sup>6</sup>, A. J. Weinheimer<sup>2</sup>, A. Wisthaler<sup>7</sup>, and R. C. Cohen<sup>1,8</sup>

<sup>1</sup>Department of Chemistry, University of California Berkeley, Berkeley, CA, USA

<sup>2</sup>Atmospheric Chemistry Division, National Center for Atmospheric Research, Boulder, CO, USA

<sup>3</sup>School of Earth and Atmospheric Sciences, Georgia Institute of Technology, Atlanta, GA, USA

<sup>4</sup>School of Engineering and Applied Science, Harvard University, Cambridge, MA, USA

<sup>5</sup>Division of Chemistry and Chemical Engineering, California Institute of Technology, Pasadena, CA, USA

<sup>6</sup>Division of Geology and Planetary Sciences, California Institute of Technology, Pasadena, CA, USA

<sup>7</sup>Institut für Ionenphysik & Angewandte Physik, University of Innsbruck, Innsbruck, Austria

<sup>8</sup>Department of Earth and Planetary Sciences, University of California Berkeley, Berkeley, CA, USA

\* now at: Chemical Sciences Division, Earth Systems Research Laboratory, National Oceanic and Atmospheric Administration, Boulder, CO, USA

\*\* now at: Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO, USA

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**Abstract.** Using measurements from the NASA Arctic Research of the Composition of the Troposphere from Aircraft and Satellites (ARCTAS) experiment, we show that methyl peroxy nitrate ( $\text{CH}_3\text{O}_2\text{NO}_2$ ) is present in concentrations of  $\sim 5$ – $15$  pptv in the springtime arctic upper troposphere. We investigate the regional and global effects of  $\text{CH}_3\text{O}_2\text{NO}_2$  by including its chemistry in the GEOS-Chem 3-D global chemical transport model. We find that at temperatures below 240 K inclusion of  $\text{CH}_3\text{O}_2\text{NO}_2$  chemistry results in decreases of up to  $\sim 20\%$  in  $\text{NO}_x$ ,  $\sim 20\%$  in  $\text{N}_2\text{O}_5$ ,  $\sim 5\%$  in  $\text{HNO}_3$ ,  $\sim 2\%$  in ozone, and increases in methyl hydrogen peroxide of up to  $\sim 14\%$ . Larger changes are observed in biomass burning plumes lofted to high altitude. Additionally, by sequestering  $\text{NO}_x$  at low temperatures,  $\text{CH}_3\text{O}_2\text{NO}_2$  decreases the cycling of  $\text{HO}_2$  to OH, resulting in a larger upper tropospheric  $\text{HO}_2$  to OH ratio. These results may impact some estimates of lightning  $\text{NO}_x$  sources as well as help explain differences between models and measurements of upper tropospheric composition.

## 1 Introduction

Non-acyl peroxy nitrates (e.g.  $\text{HO}_2\text{NO}_2$ ,  $\text{CH}_3\text{O}_2\text{NO}_2$ ) are weakly bound molecules that play a role in the chemistry of the troposphere where it is cold (Slusher et al., 2002; Murphy et al., 2004; Kim et al., 2007) or where peroxy radicals and  $\text{NO}_x$  ( $\text{NO}_x = \text{NO} + \text{NO}_2$ ) have especially high concentrations (Spencer et al., 2009). Initial observations and calculations focused on understanding the role these molecules play in the stratospheric  $\text{HO}_x$  ( $\text{HO}_x = \text{OH} + \text{HO}_2$ ) balance (e.g. Wennberg et al., 1999). More recently, in-situ observations of non-acyl peroxy nitrates in the troposphere (Slusher et al., 2002; Murphy et al., 2004; Kim et al., 2007; Spencer et al., 2009) have resulted in increased interest in the role of these compounds in  $\text{NO}_x$  and  $\text{HO}_x$  budgets in the lower troposphere. During the NCAR Tropospheric Ozone Production about the Spring Equinox (TOPSE) experiment (Atlas et al., 2003), measurements in the Arctic upper troposphere, where temperatures were on average  $\sim 230$  K, showed that non-acyl peroxy nitrates, primarily  $\text{HO}_2\text{NO}_2$ , were on average, 30 % of  $\text{NO}_y$  ( $\text{NO}_y = \text{NO} + \text{NO}_2 + \text{HO}_2\text{NO}_2 + \text{CH}_3\text{O}_2\text{NO}_2 + \text{HNO}_3 + \text{HONO} + \text{acyl peroxy nitrates} + \text{organic nitrates} + \text{NO}_3 + 2\text{N}_2\text{O}_5$ ) (Murphy et al., 2004). These observations imply that  $\text{HO}_2\text{NO}_2$  represents a significant sink of  $\text{HO}_x$  and acts as a large reservoir of  $\text{NO}_x$  in the Arctic during winter and spring. Measurements from



Correspondence to: R. C. Cohen  
(rccohen@berkeley.edu)

**Table 1.** Measurements used in this analysis to constrain the photostationary state model. XNO<sub>2</sub> refers to the sum of NO<sub>2</sub> and the fraction of CH<sub>3</sub>O<sub>2</sub>NO<sub>2</sub> + HO<sub>2</sub>NO<sub>2</sub> that thermally dissociate in the inlet of the LIF instrument.

Species	Method	Reference
NO, O <sub>3</sub>	Chemiluminescence	Weinheimer et al. (1994)
XNO <sub>2</sub>	LIF <sup>a</sup>	Thornton et al. (2000); Cleary et al. (2002)
Pernitric acid, peracetic acid, methyl hydrogen peroxide	CIMS <sup>b</sup>	Crouse et al. (2006, 2009) St. Clair et al. (2010)
Acetone	PTR-MS <sup>c</sup>	Wisthaler et al. (2002)
Acetaldehyde	GC-MS <sup>d</sup>	Apel et al. (2003)
Peroxyacetyl nitrate	CIMS <sup>b</sup>	Slusher et al. (2004); Kim et al. (2007)
CH <sub>4</sub>	TDLAS <sup>e</sup>	Sachse et al. (1987); Diskin et al. (2002)
OH, HO <sub>2</sub>	LIF <sup>a</sup> CIMS <sup>b</sup>	Faloona et al. (2004); Cantrell et al. (2003a)
UV photolytic frequencies	Spectral radiometry	Shetter and Müller (1999)

<sup>a</sup> Laser Induced Fluorescence <sup>b</sup> Chemical ionization mass spectrometry <sup>c</sup> Proton transfer reaction mass spectrometry <sup>d</sup> Gas chromatography – mass spectrometry  
<sup>e</sup> Tunable diode laser absorption spectroscopy

the NASA Intercontinental Chemical Transport Experiment-North America (INTEX-NA) demonstrated that HO<sub>2</sub>NO<sub>2</sub> is present in the mid-latitude upper troposphere at mixing ratios of approximately 76 pptv between 8 and 9 km, accounting for about 5 % of NO<sub>y</sub> and 10 % of the local HO<sub>x</sub> sink (Kim et al., 2007).

HO<sub>2</sub>NO<sub>2</sub> is formed by the association reaction of HO<sub>2</sub> and NO<sub>2</sub> and methyl peroxy nitrate (CH<sub>3</sub>O<sub>2</sub>NO<sub>2</sub>) is formed by the analogous association reaction of CH<sub>3</sub>O<sub>2</sub> with NO<sub>2</sub>. Although CH<sub>3</sub>O<sub>2</sub> is the second most abundant peroxy radical in the atmosphere (after HO<sub>2</sub>), much less attention has been devoted to CH<sub>3</sub>O<sub>2</sub>NO<sub>2</sub> chemistry. To our knowledge the indirect measurement of the sum of HO<sub>2</sub>NO<sub>2</sub> and CH<sub>3</sub>O<sub>2</sub>NO<sub>2</sub> during the TOPSE campaign by Murphy et al. (2004) is the only previous in-situ evidence for CH<sub>3</sub>O<sub>2</sub>NO<sub>2</sub>. CH<sub>3</sub>O<sub>2</sub>NO<sub>2</sub> chemistry has been previously considered in some box and one dimensional models. Thompson et al. (1997) used a 1-D tropospheric chemical model and upper tropospheric measurements from the Pacific Exploratory Mission in the Western Pacific Ocean (PEM-West B) and predicted a mean concentration of 27 pptv for CH<sub>3</sub>O<sub>2</sub>NO<sub>2</sub> at 10 km in the mid-latitudes (35°–45° N) during February and March. During TOPSE, a steady-state model indicated that at temperatures around 250 K CH<sub>3</sub>O<sub>2</sub>NO<sub>2</sub> should be present at average concentrations of 70 pptv (at 40°–60° N) and 27 pptv (at 60°–85° N) (Cantrell et al., 2003b). Here we present experimental evidence from observations during the Arctic Research of the Composition of the Troposphere from Aircraft and Satellites (ARCTAS) experiment for the presence of CH<sub>3</sub>O<sub>2</sub>NO<sub>2</sub>. We use the GEOS-Chem (Bey et al., 2001) 3-D chemical transport model to investigate the effects of CH<sub>3</sub>O<sub>2</sub>NO<sub>2</sub> chemistry on the distribution of NO<sub>x</sub>, O<sub>3</sub>, NO<sub>y</sub>, and HO<sub>y</sub> (HO<sub>y</sub> = OH + HO<sub>2</sub> + HONO + HO<sub>2</sub>NO<sub>2</sub> + CH<sub>3</sub>OOH + 2 H<sub>2</sub>O<sub>2</sub>) species. We find that at temperatures below 240 K, the addition of CH<sub>3</sub>O<sub>2</sub>NO<sub>2</sub> chemistry to GEOS-Chem decreases regional concentrations of NO<sub>x</sub> by 20 % and of O<sub>3</sub> by 2 %. Addition-

ally, concentrations of N<sub>2</sub>O<sub>5</sub> decrease by ~20 % and methyl hydrogen peroxide concentrations increase by ~14 %.

## 2 Measurements

The ARCTAS measurement campaign has been described in detail by Jacob et al. (2010). Here we focus on the spring portion of ARCTAS (ARCTAS-A) which took place 1–19 April 2008. ARCTAS-A consisted of two transit flights between Palmdale, CA and Fairbanks, Alaska (65° N, 148° W) and seven arctic flights. The arctic flights included three local flights as well as flights to and from Thule, Greenland (77° N, 69° W) and Iqaluit, Nunavut (64° N, 69° W). In this analysis we only consider data collected north of 55° N.

The payload of the DC-8 consisted of an extensive suite of gas phase and aerosol measurements (Jacob et al., 2010). In our analysis we use the measurements listed in Table 1. All data are available in a public archive (<http://www-air.larc.nasa.gov/cgi-bin/arcstat-c>). Although OH and HO<sub>2</sub> were measured both by the NCAR chemical ionization mass spectrometer (Cantrell et al., 2003a) and the Pennsylvania State laser induced fluorescence (LIF) techniques (Faloona et al., 2004), we use the LIF OH and HO<sub>2</sub> measurements in our model due to the more extensive coverage at high altitudes.

The core measurements for this analysis are from the UC Berkeley nitrogen oxides instrument. Briefly, total peroxy nitrates (Σ PNs), total alkyl and multifunctional nitrates (Σ ANs), and NO<sub>2</sub> were measured using the Thermal Dissociation-Laser Induced Fluorescence (TD-LIF) instrument described in detail by Wooldridge et al. (2010). NO<sub>2</sub> is measured using laser induced fluorescence (Thornton et al., 2000) with supersonic expansion (Cleary et al., 2002). A 7 kHz, Q-switched, frequency doubled Nd:YAG laser pumps a tunable dye laser utilizing a mixture of pyrromethene 597 in isopropanol. This produces narrowband radiation

(0.06 cm<sup>-1</sup>) at 585 nm. The laser light is focused through two multipass white cells and the red-shifted fluorescence (wavelengths long of 700 nm) is detected using a red sensitive photomultiplier tube (Hamamatsu H7421-50). Prompt scatter is eliminated using time gated detection and scattered light with wavelengths less than 700 nm is rejected by band-pass filters. Fluorescence counts are collected at 4 Hz and averaged to one second for reporting to the data archive. We tune the dye laser on and off an isolated rovibronic feature of the jet-cooled NO<sub>2</sub> at 585 nm. The frequency is held at the peak of the feature for 9 s and then moved to the off-line position in the continuum absorption of NO<sub>2</sub> for 3 s. The difference between these two signals is directly proportional to the NO<sub>2</sub> mixing ratio. The ratio between the peak and background NO<sub>2</sub> fluorescence is 10 to 1 at 760 torr backing pressure behind the expansion nozzle. The detection cells are kept at a pressure of approximately 0.2 torr. Calibration is performed at least every two hours during a level flight leg using a 4.5 ppm NO<sub>2</sub> reference standard diluted to ~2–8 ppbv in zero air. Stability of the NO<sub>2</sub> reference is verified by comparing a library of 6–8 different NO<sub>2</sub> standards approximately twice a year. These standards have been observed to remain stable for up to 5 years and to be accurate at atmospherically relevant mixing ratios to within 1 % (Bertram et al., 2005). As described in Thornton et al. (2000), correction for fluorescence quenching by water is made using the DLH measurements (Sachse et al., 1987; Diskin et al., 2002).

The configuration of the instrument for ARCTAS consisted of two detection cells. Sample flow was directed through a short (18 cm) inlet heated to approximately 25 °C and then split into two sampling lines. Two-thirds of the flow is directed down 154.5 cm of PFA tubing at cabin temperature before splitting in two. Half of this flow is directed to detection cell 1 for ambient NO<sub>2</sub> measurement. The other half is heated in a quartz tube at 200 °C to thermally dissociate peroxy nitrates and then passes through PFA tubing to detection cell 2. The remaining third of the sample flow is passed directly into a heated quartz tube (375 °C) followed by PFA tubing for Σ ANs detection in detection cell 2. NO<sub>2</sub> was measured continuously in cell 1 while cell 2 alternately sampled the NO<sub>2</sub> + Σ PNs signal (50 % of the time) and the NO<sub>2</sub> + Σ PNs + Σ ANs signal (50 % of the time).

During ARCTAS, NO<sub>2</sub> was also measured by photolytic conversion to NO with detection via chemiluminescence from the reaction of NO and ozone (Weinheimer et al., 1994). For the one minute merged data (version 11) the measurements agree within the stated uncertainties. A linear least-squares non-weighted fit (as in Cantrell, 2008) of the chemiluminescence data versus the LIF data resulted in a slope of 0.95 ± 0.01 with an intercept of -8.1 ± 0.8 pptv and an R<sup>2</sup> value of 0.95.

### 3 Observational evidence of CH<sub>3</sub>O<sub>2</sub>NO<sub>2</sub>

Methyl peroxy nitrate is weakly bound (~95 kJ mol<sup>-1</sup>) and calculations (performed after ARCTAS was completed) suggest that it dissociates with high efficiency in the inlet lines of the TD-LIF instrument after which it is detected in the NO<sub>2</sub> channel. The interference from CH<sub>3</sub>O<sub>2</sub>NO<sub>2</sub> is expected to affect both the LIF and chemiluminescence NO<sub>2</sub> measurements. It is likely that past measurements of NO<sub>2</sub> in the upper troposphere and arctic are subject to this interference from CH<sub>3</sub>O<sub>2</sub>NO<sub>2</sub>. This may explain discrepancies between observed and modeled upper tropospheric NO<sub>2</sub> in past experiments (e.g. Crawford et al., 1996). Additionally, it is consistent with the improvement between upper tropospheric measured and modeled NO<sub>2</sub> observed by Bradshaw et al. (1999) between the 1991 PEM-West-A experiment and 1996 PEM-Tropics-A experiment when the inlet was redesigned to decrease the residence time to 40 ms (from 2 s). Here we focus on CH<sub>3</sub>O<sub>2</sub>NO<sub>2</sub> and its behavior in the LIF instrument as it was configured during ARCTAS. In what follows we refer to this measurement as XNO<sub>2</sub> to indicate that it is a measurement of the sum of NO<sub>2</sub> and a fraction of these thermally labile nitrogen compounds.

Given a 300 K cabin temperature (approximate mean cabin temperature during ARCTAS) and a pressure of 300 torr, the thermal decomposition lifetime of CH<sub>3</sub>O<sub>2</sub>NO<sub>2</sub> is 700 ms, while that of HO<sub>2</sub>NO<sub>2</sub> is 17.9 s. Although the residence time of an ambient sample in our detection system is quite short (~350–850 ms), we calculate that between 48 and 77 % of CH<sub>3</sub>O<sub>2</sub>NO<sub>2</sub> and 3 to 6 % of HO<sub>2</sub>NO<sub>2</sub> thermally dissociate prior to reaching the NO<sub>2</sub> detection cell. HO<sub>2</sub>NO<sub>2</sub> dissociation is minimal and results in a median calculated NO<sub>2</sub> interference of less than 1 ppt (6 % of the XNO<sub>2</sub> signal) and a maximum absolute interference during a 1 minute period of 10.3 ppt (19 % of the NO<sub>2</sub> signal). This molecule is detected with near unit efficiency in the Σ PNs channel as described previously (Murphy et al., 2004; Wooldridge et al., 2010).

We calculate the ambient CH<sub>3</sub>O<sub>2</sub>NO<sub>2</sub> concentration using an instantaneous photostationary state model subject to the constraint that the sum of the model NO<sub>2</sub> and the fractions of HO<sub>2</sub>NO<sub>2</sub> and CH<sub>3</sub>O<sub>2</sub>NO<sub>2</sub> that dissociate in the LIF inlet are equal to the LIF measurement of XNO<sub>2</sub>. We used measured concentrations of HO<sub>2</sub>NO<sub>2</sub> to calculate the contribution of HO<sub>2</sub>NO<sub>2</sub> to the XNO<sub>2</sub> measurement. Since the validity of the photostationary state assumption requires that the source and sink reactions of a molecule vary slowly in comparison to the lifetime of that molecule, we perform this calculation only when the lifetime of CH<sub>3</sub>O<sub>2</sub>NO<sub>2</sub> is less than 12 h, or there is greater than 20 h of sunlight per day as in Murphy et al. (2004). Additionally, we filter the data to exclude locations where tropospheric composition has been recently perturbed. These include times when the DC-8 sampled fresh NO<sub>x</sub> emissions (defined as NO<sub>x</sub>/NO<sub>y</sub> > 0.2 and when NO was more than ±3 standard deviations of the median value within ±0.5 km altitude), ozone

**Table 2.** Reactions and rates used in the photostationary state model.

Reaction	Rate Constant
1 CH <sub>4</sub> + OH + O <sub>2</sub> → CH <sub>3</sub> O <sub>2</sub> + H <sub>2</sub> O	2.45 × 10 <sup>-12</sup> × exp(-1775/T) <sup>a</sup>
2 CH <sub>3</sub> C(O)O <sub>2</sub> + NO → CH <sub>3</sub> O <sub>2</sub> + CO <sub>2</sub> + NO <sub>2</sub>	8.1 × 10 <sup>-12</sup> × exp(270/T) <sup>a</sup>
3 CH <sub>3</sub> C(O)CH <sub>3</sub> + hν + 2 O <sub>2</sub> → CH <sub>3</sub> C(O)O <sub>2</sub> + CH <sub>3</sub> O <sub>2</sub>	Measured
4 CH <sub>3</sub> C(O)O <sub>2</sub> + CH <sub>3</sub> C(O)O <sub>2</sub> + 2 O <sub>2</sub> → 2 CH <sub>3</sub> O <sub>2</sub> + 2 CO <sub>2</sub> + O <sub>2</sub>	2.9 × 10 <sup>-12</sup> × exp(500/T) <sup>a</sup>
5 CH <sub>3</sub> OOH + OH $\xrightarrow{70\%}$ CH <sub>3</sub> O <sub>2</sub> + H <sub>2</sub> O	3.8 × 10 <sup>-12</sup> × exp(200/T) <sup>a</sup>
6 CH <sub>3</sub> C(O)H + hν + O <sub>2</sub> → CH <sub>3</sub> O <sub>2</sub> + HCO	Measured
7 CH <sub>3</sub> O <sub>2</sub> NO <sub>2</sub> + hν → CH <sub>3</sub> O <sub>2</sub> + NO <sub>2</sub>	Assumed to be equal to measured HO <sub>2</sub> NO <sub>2</sub> value
8 CH <sub>3</sub> O <sub>2</sub> NO <sub>2</sub> + hν → CH <sub>3</sub> O + NO <sub>3</sub>	Assumed to be equal to measured HO <sub>2</sub> NO <sub>2</sub> value
9 CH <sub>3</sub> O <sub>2</sub> + NO → CH <sub>3</sub> O + NO <sub>2</sub>	2.8 × 10 <sup>-12</sup> × exp(300/T) <sup>a</sup>
10 CH <sub>3</sub> O <sub>2</sub> + HO <sub>2</sub> → Products	3.8 × 10 <sup>-13</sup> × exp(780/T) <sup>b</sup>
11 CH <sub>3</sub> O <sub>2</sub> + CH <sub>3</sub> C(O)O <sub>2</sub> → Products	2.0 × 10 <sup>-12</sup> × exp(500/T) <sup>a</sup>
12 CH <sub>3</sub> O <sub>2</sub> + CH <sub>3</sub> O <sub>2</sub> → Products	9.5 × 10 <sup>-14</sup> × exp(390/T) <sup>a</sup>
13 CH <sub>3</sub> O <sub>2</sub> + NO <sub>2</sub> + M ↔ CH <sub>3</sub> O <sub>2</sub> NO <sub>2</sub> + M	Low Pressure Limit = 1.0 × 10 <sup>-30</sup> × (T/300) <sup>-4.8</sup> High Pressure Limit = 7.2 × 10 <sup>-12</sup> × (T/300) <sup>-2.1</sup> K <sub>eq</sub> = 9.5 × 10 <sup>-29</sup> × exp(11234/T) <sup>a</sup>
14 CH <sub>3</sub> C(O)O <sub>2</sub> NO <sub>2</sub> + hν → CH <sub>3</sub> C(O)O <sub>2</sub> + NO <sub>2</sub>	Measured
15 CH <sub>3</sub> C(O)O <sub>2</sub> NO <sub>2</sub> ↔ CH <sub>3</sub> C(O)O <sub>2</sub> + NO <sub>2</sub>	Low Pressure Limit = 9.7 × 10 <sup>-29</sup> × (T/300) <sup>-5.6</sup> High Pressure Limit = 9.3 × 10 <sup>-12</sup> × (T/300) <sup>-1.5</sup> K <sub>eq</sub> = 9.0 × 10 <sup>-29</sup> × exp(14 000/T) <sup>a</sup>
16 CH <sub>3</sub> C(O)OOH + OH → CH <sub>3</sub> C(O)O <sub>2</sub> + H <sub>2</sub> O	3.7 × 10 <sup>-12c</sup>
17 CH <sub>3</sub> C(O)H + OH + O <sub>2</sub> → CH <sub>3</sub> C(O)O <sub>2</sub> + H <sub>2</sub> O	4.7 × 10 <sup>-12</sup> × exp(345/T) <sup>b</sup>
18 CH <sub>3</sub> C(O)O <sub>2</sub> + HO <sub>2</sub> → Products	5.2 × 10 <sup>-13</sup> × exp(980/T) <sup>b</sup>

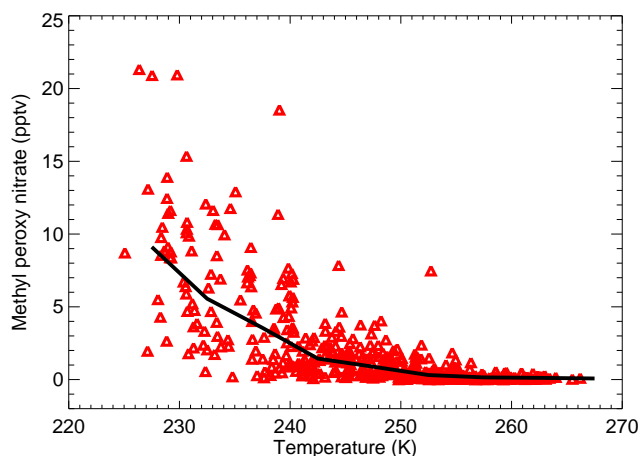
<sup>a</sup> JPL 2006 (Sander et al., 2006); <sup>b</sup> Atkinson et al. (2006) (web version last updated 2009 [http://www.iupac-kinetic.ch.cam.ac.uk/show\\_datasheets.php?category=gas-phase+organics%3a+hox+%2b+voc+%28c1-c3%29](http://www.iupac-kinetic.ch.cam.ac.uk/show_datasheets.php?category=gas-phase+organics%3a+hox+%2b+voc+%28c1-c3%29)); <sup>c</sup> Master Chemical Mechanism v3.1 (Saunders et al., 2003)

depletion events (O<sub>3</sub> < 20 ppb), stratospheric influences (defined as O<sub>3</sub>/CO > 0.75), and solar zenith angle greater than 85 degrees. These restrictions exclude measurements from the coldest temperatures/highest altitudes sampled during ARCTAS: conditions under which we would expect high concentrations of CH<sub>3</sub>O<sub>2</sub>NO<sub>2</sub>.

The reactions included in the photostationary state calculation are shown in Table 2. All measured values are from the archived one minute merged data, version 11. In addition to the XNO<sub>2</sub> measurement, concentrations of species listed in Table 1 were used to constrain the model. The use of the measured OH and HO<sub>2</sub> concentrations enables us to exclude HO<sub>x</sub> source reactions from our photostationary state model. As the IUPAC recommended UV cross sections for CH<sub>3</sub>O<sub>2</sub>NO<sub>2</sub> (Atkinson et al., 2006) are identical to HO<sub>2</sub>NO<sub>2</sub> (Atkinson et al., 2004), we set the UV photolysis of CH<sub>3</sub>O<sub>2</sub>NO<sub>2</sub> equal to the measured UV photolysis rate of HO<sub>2</sub>NO<sub>2</sub>. We do not consider infrared overtone photolysis of CH<sub>3</sub>O<sub>2</sub>NO<sub>2</sub> due to the shorter thermal decomposition lifetime of CH<sub>3</sub>O<sub>2</sub>NO<sub>2</sub> and the lower expected cross section of C-H overtones (Nizkorodov et al., 2005; Vaida, 2009). The model is run to steady state concentrations (±0.001 %) for peroxyacetyl radical, methyl peroxy radical, and CH<sub>3</sub>O<sub>2</sub>NO<sub>2</sub>. We do not attempt to fill in missing data points from any of the measured species and calculate

concentrations for the 480 one minute averaged data points which meet our selection criteria.

Uncertainties in our model calculations of NO<sub>2</sub> and CH<sub>3</sub>O<sub>2</sub>NO<sub>2</sub> will be a combination of systematic and random uncertainties in the measured concentrations and systematic uncertainties in the photolysis rates, the rate constants, and the estimated residence time in our instrument prior to detection. Uncertainties in the rate constants for CH<sub>3</sub>O<sub>2</sub>NO<sub>2</sub> formation and dissociation and in the instrument residence time will have the largest systematic effect on our results. In our calculation we use the JPL-2006 (Sander et al., 2006) rate recommendations for CH<sub>3</sub>O<sub>2</sub>NO<sub>2</sub> reactions. This recommendation is based on the recent work of Golden (2005), who has re-evaluated the data for formation and dissociation of CH<sub>3</sub>O<sub>2</sub>NO<sub>2</sub>. This re-evaluation includes the new measurements of the association reaction of CH<sub>3</sub>O<sub>2</sub> and NO<sub>2</sub> by Bacak et al. (2006). The measurement of Bacak et al. (2006) at 223 K represents the first measurements of the rate constant below 253 K, thus significantly reducing the uncertainty in this reaction at low temperatures. Adjusting the uncertainties to the JPL-2006 one sigma values for the rate constants of formation and decomposition of CH<sub>3</sub>O<sub>2</sub>NO<sub>2</sub> results in changes to the calculated NO<sub>2</sub> values of ~ ±23 % (~1.2 ppt) and of ∓40 % (~2.3 ppt) for CH<sub>3</sub>O<sub>2</sub>NO<sub>2</sub> in the temperature range of 230–235 K. This range of NO<sub>2</sub> concentrations is

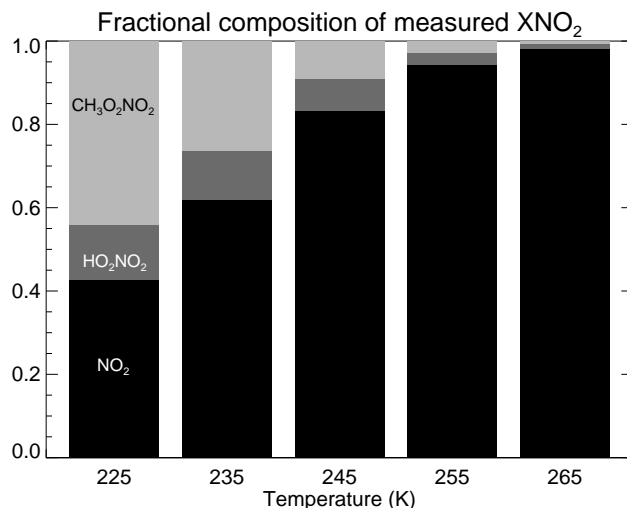


**Fig. 1.** Methyl peroxy nitrate concentration inferred from observations. The black line represents temperature binned median values.

within the uncertainty of a simpler calculation of steady state  $\text{NO}_2$  using only the measured  $\text{NO}_2$  photolysis rate and the  $\text{NO}$ , ozone, and  $\text{HO}_2$  concentrations.

The residence time in the UC Berkeley LIF was determined in the laboratory after ARCTAS was completed by varying inlet and outlet pressures to simulate aircraft conditions and measuring the flows. Due to the difficulties in simulating aircraft conditions in the lab, we assign an uncertainty of  $\pm 25\%$  to our residence time. An increase of 25% in the residence time leads to decreases of approximately 10% in both  $\text{NO}_2$  and  $\text{CH}_3\text{O}_2\text{NO}_2$  concentrations at 230–235 K. A decrease in residence time of 25% results in  $\sim 10\%$  increases of  $\text{NO}_2$  and  $\text{CH}_3\text{O}_2\text{NO}_2$  in the same temperature range. A decrease in residence time results in an increase in both  $\text{NO}_2$  and  $\text{CH}_3\text{O}_2\text{NO}_2$  because the decreased residence time results in smaller fractions of  $\text{CH}_3\text{O}_2\text{NO}_2$  and  $\text{HO}_2\text{NO}_2$  that dissociate in the inlet. Since we force the sum of dissociated  $\text{CH}_3\text{O}_2\text{NO}_2$ , dissociated  $\text{HO}_2\text{NO}_2$ , and calculated  $\text{NO}_2$  to equal the measured  $\text{XNO}_2$ , the decrease in the fractions of  $\text{CH}_3\text{O}_2\text{NO}_2$  and  $\text{HO}_2\text{NO}_2$  that dissociate results in a larger concentration of  $\text{NO}_2$  and thus a higher calculated steady state  $\text{CH}_3\text{O}_2\text{NO}_2$ .

The concentrations of  $\text{CH}_3\text{O}_2\text{NO}_2$  calculated by the photostationary state model and constrained by the  $\text{XNO}_2$  observations reach values of up to  $\sim 5$ – $15$  pptv in the coldest conditions sampled during ARCTAS (Fig. 1). It is probable that larger concentrations of  $\text{CH}_3\text{O}_2\text{NO}_2$  were present during ARCTAS in conditions under which our photostationary state assumption fails. Under these conditions, the median  $\text{CH}_3\text{O}_2\text{NO}_2$  mixing ratio is  $\sim 1.6$  times larger than that of  $\text{NO}_2$ . As shown in Fig. 2, at temperatures below 240 K,  $\text{CH}_3\text{O}_2\text{NO}_2$  ranges from  $\sim 27$ – $43\%$  of  $\text{XNO}_2$  while thermal dissociation of  $\text{HO}_2\text{NO}_2$  contributes  $\sim 11$ – $14\%$ . The resulting  $\text{NO}_2$  shows improved agreement with  $\text{NO}_2$  predicted from measured  $\text{NO}$ ,  $\text{HO}_2$ , and  $\text{NO}_2$  photolysis values at tem-



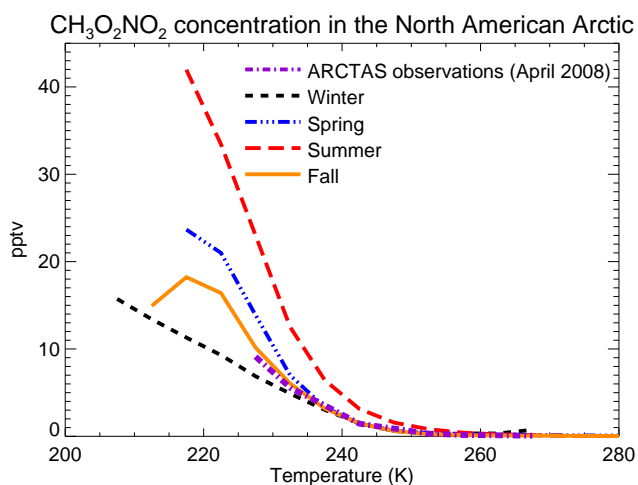
**Fig. 2.** Fractional composition of the  $\text{XNO}_2$  measured by the UC Berkeley LIF nitrogen oxides instrument calculated using the photostationary state model constrained to total measured  $\text{XNO}_2$ . We estimate that 48–77% of  $\text{CH}_3\text{O}_2\text{NO}_2$  and 3–6% of  $\text{HO}_2\text{NO}_2$  dissociate in the inlet prior to detection.

peratures  $\sim 245$  K and below (not shown). Since  $\text{CH}_3\text{O}_2\text{NO}_2$  is approximately equal to  $\text{NO}_2$  at temperatures below 240 K, it serves as an important  $\text{NO}_x$  reservoir that will release  $\text{NO}_x$  when the air mass warms, potentially doubling the  $\text{NO}_2$  concentration. This source of  $\text{CH}_3\text{O}_2$  and  $\text{NO}_2$  radicals will increase ozone production and affect  $\text{NO}_x$  and  $\text{HO}_x$  chemistry. In order to investigate this more completely, we added  $\text{CH}_3\text{O}_2\text{NO}_2$  chemistry to the global 3-D chemical transport model GEOS-Chem.

#### 4 Global 3-D CTM model results

The GEOS-Chem model (version 08-02-02) was run at  $2 \times 2.5$  degree resolution. The standard chemistry in the model is described in detail in Mao et al. (2010). Two separate runs were conducted: one with  $\text{CH}_3\text{O}_2\text{NO}_2$  reactions added to the standard chemistry (hereinafter referred to as the methyl peroxy nitrate or MPN case) and one with only the standard chemistry (hereinafter referred to as the base case). The  $\text{CH}_3\text{O}_2\text{NO}_2$  reactions consisted of Reactions (R7), (R8) and (R13) from Table 2. As in the photostationary state model, photolysis of  $\text{CH}_3\text{O}_2\text{NO}_2$  was calculated assuming that the UV cross sections were equal to those of  $\text{HO}_2\text{NO}_2$  and that IR photolysis of  $\text{CH}_3\text{O}_2\text{NO}_2$  resulting from vibrational overtone excitation was negligible.

Both models were run from January–December 2007 to remove memory of the initialization. We analyze output for January–December 2008. Twenty-four hour averaged concentrations are saved for both the first and second half of each month. In this analysis we focus on the resulting changes in tropospheric concentrations to  $\text{NO}_x$ , ozone,  $\text{N}_2\text{O}_5$ ,  $\text{HO}_2\text{NO}_2$ ,



**Fig. 3.** Temperature binned mean values of the GEOS-Chem modeled  $\text{CH}_3\text{O}_2\text{NO}_2$  24 h average concentrations over the North American Arctic for each season.

$\text{HNO}_3$ , and methyl hydrogen peroxide. We choose these species as examples to illustrate that due to the highly coupled, non-linear relationship between  $\text{NO}_x$  and  $\text{HO}_x$ , altering  $\text{NO}_x$  concentrations by including  $\text{CH}_3\text{O}_2\text{NO}_2$  chemistry changes: the cycling of  $\text{NO}_x$  (and thus ozone concentrations), both short ( $\text{N}_2\text{O}_5$ ,  $\text{HO}_2\text{NO}_2$ ) and long-term ( $\text{HNO}_3$ )  $\text{NO}_x$  reservoirs and sinks, and  $\text{HO}_x$  reservoirs ( $\text{CH}_3\text{OOH}$ ). We do not attempt a thorough budget analysis of the changes in all of these species; our goal is to illustrate how changes resulting from inclusion of  $\text{CH}_3\text{O}_2\text{NO}_2$  chemistry affect tropospheric composition. Significant changes in tropospheric composition, particularly at cold temperatures, result when  $\text{CH}_3\text{O}_2\text{NO}_2$  chemistry is included. We present seasonal mean results for the North American Arctic (defined here as  $175^\circ\text{W}$ – $35^\circ\text{W}$  and  $65^\circ\text{N}$ – $85^\circ\text{N}$ ) and summertime (June, July, August) results from the tropics (defined here as  $180^\circ\text{W}$ – $180^\circ\text{E}$  and  $20^\circ\text{S}$ – $20^\circ\text{N}$ ). We restrict this analysis to the troposphere by only using results in the model's vertical layers below the layer containing the tropopause.

#### 4.1 North American Arctic

As shown in Fig. 3, the mean value for modeled  $\text{CH}_3\text{O}_2\text{NO}_2$  in the coldest conditions ( $\sim 220\text{ K}$ ) during the summertime (June, July, August) in the North American Arctic is  $\sim 40$  pptv. During winter (December, January, February), concentrations are lower due to decreased production. The spring (March, April, May) concentrations are slightly higher than the concentrations inferred from the ARCTAS observations of  $\text{XNO}_2$  (Sect. 3). We expect that part of this discrepancy is due to exclusion of non-photostationary state conditions from the ARCTAS observations.  $\text{CH}_3\text{O}_2\text{NO}_2$  acts as a  $\text{NO}_x$  reservoir and including it in the GEOS-Chem model results in  $\sim 14$ – $23\%$  less  $\text{NO}_x$  ( $\sim 12$  pptv in the summer)

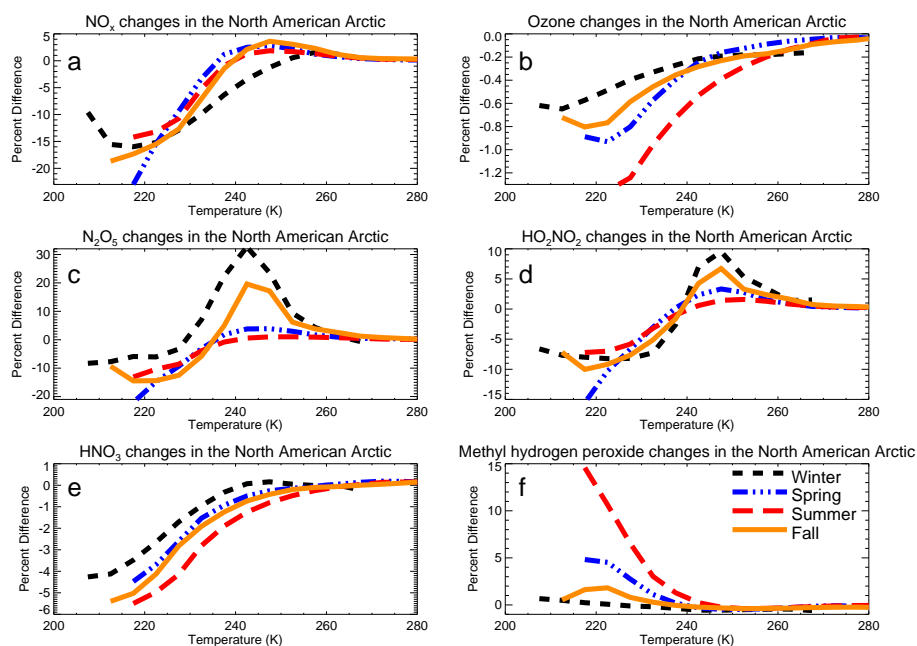
(Fig. 4a) as compared to the base case. As a result, in the summer, when photochemistry is most active, ozone is reduced by 1.2 % (1.3 ppbv) (Fig. 4b). In the winter, ozone is reduced by 0.6 % (0.5 ppbv). Although  $\text{NO}_y$  concentrations remain unchanged, substantial differences in the partitioning of  $\text{NO}_y$  is observed. At the coldest temperatures  $\text{N}_2\text{O}_5$  concentrations are reduced by  $\sim 10$ – $20\%$  ( $\sim 0.2$  pptv) (Fig. 4c) due to sequestration of  $\text{NO}_2$  by  $\text{CH}_3\text{O}_2\text{NO}_2$ . At temperatures above  $\sim 230$ – $240\text{ K}$ ,  $\text{CH}_3\text{O}_2\text{NO}_2$  causes increases in  $\text{N}_2\text{O}_5$  of up to 20 % in the fall (September, October, November) and 30 % in winter. Increases in  $\text{HO}_2\text{NO}_2$  concentrations are also seen in the fall and winter (Fig. 4d). These increases result from an increase in chemical production of  $\text{N}_2\text{O}_5$  and  $\text{HO}_2\text{NO}_2$  in the MPN case relative to the base case. The increase in chemical production is due to increased  $\text{NO}_2$  concentrations (at 240 K  $\text{NO}_2$  is 20 % larger in the winter and 16 % larger in fall). This increase in  $\text{NO}_2$  is presumably due to thermal dissociation of  $\text{CH}_3\text{O}_2\text{NO}_2$ . It should be noted that although these are large relative changes, they represent absolute changes of generally less than 1 pptv.

By sequestering  $\text{NO}_x$ ,  $\text{CH}_3\text{O}_2\text{NO}_2$  reduces  $\text{NO}$  concentrations resulting in a decreased conversion of  $\text{HO}_2$  to  $\text{OH}$ . Consequently,  $\text{OH}$  concentrations are lower (not shown). These reductions in  $\text{NO}_x$  and  $\text{OH}$  by  $\text{CH}_3\text{O}_2\text{NO}_2$  chemistry result in up to 4 % less  $\text{HNO}_3$  ( $\sim 6$  pptv) in the winter and 5.5 % less  $\text{HNO}_3$  ( $\sim 15$  pptv) in the summer (Fig. 4e). The  $\text{HO}_y$  species methyl hydrogen peroxide shows increases up to 14 % ( $\sim 3$  pptv) at  $\sim 220\text{ K}$  in the summertime (Fig. 4f). Smaller increases occur at other times of the year. The changes in methyl hydrogen peroxide concentrations are due to increases in chemical production (resulting from higher  $\text{HO}_2$  concentrations), increases in lifetime due to the lower  $\text{OH}$  concentrations, and changes in the concentrations transported into the region. At 220 K, chemical production is increased  $\sim 4\%$  in the MPN case relative to the base case in the spring and in the summer it is increased by  $\sim 10\%$ . The lifetime of methyl hydrogen peroxide in the MPN case relative to the base case increases by  $\sim 6\%$  in the spring and  $\sim 9\%$  in the summer.

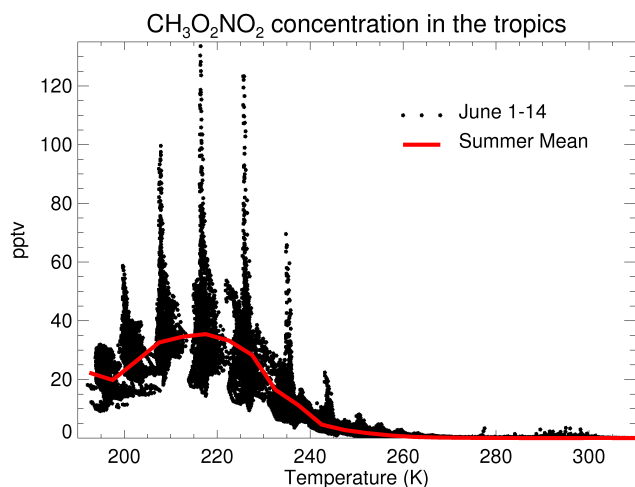
#### 4.2 Tropics

Although overall results from the tropics are similar to the results in the North American Arctic there are two distinct differences. First, temperatures in the upper troposphere of the tropics are lower than in the mid latitudes and polar regions due to the higher tropopause. Consequently,  $\text{CH}_3\text{O}_2\text{NO}_2$  concentrations peak at temperatures of  $\sim 215\text{ K}$  and decrease at lower temperatures (Fig. 5) as do the differences between the base and MPN cases (Figs. 6 and 7). The decrease occurs because of a reduction in  $\text{CH}_3\text{O}_2$  formation due to the slower rate of  $\text{OH} + \text{CH}_4$  at colder temperatures. The second important difference from the North American Arctic is the presence of large modeled spikes in  $\text{CH}_3\text{O}_2\text{NO}_2$  concentrations (and the resulting large spikes in differences between





**Fig. 4.** Differences between the GEOS-Chem base case and MPN case ( $((\text{MPN}-\text{BASE})/\text{BASE}) \times 100$ ) over the North American Arctic versus temperature for (a)  $\text{NO}_x$ , (b) ozone, (c)  $\text{N}_2\text{O}_5$ , (d)  $\text{HO}_2\text{NO}_2$ , (e)  $\text{HNO}_3$ , and (f) methyl hydrogen peroxide. These results are temperature binned means of 24 h averaged concentrations.



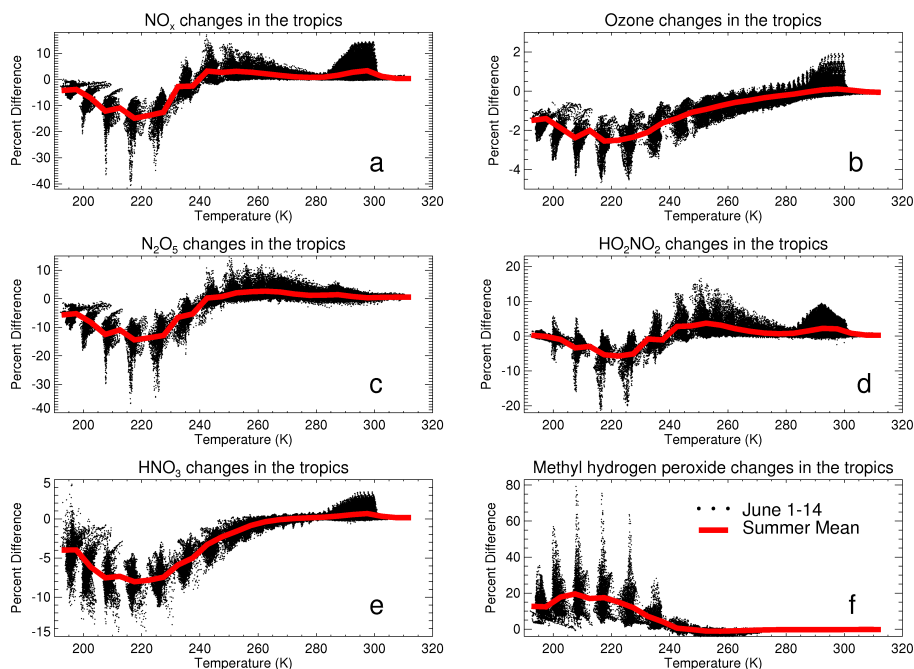
**Fig. 5.** Tropospheric concentrations of  $\text{CH}_3\text{O}_2\text{NO}_2$  versus temperature over the tropics. The individual points are the 24 h average value of 1–14 June 2008. The red line is the summer mean concentration. The regular temperature intervals at low temperatures are a result of decreasing vertical resolution in the model at increasing altitudes.

the base and MPN cases) on the otherwise smooth curve that has the temperature dependence of  $\text{CH}_3\text{O}_2\text{NO}_2$  chemistry. These spikes are due to elevated concentrations of  $\text{CH}_3\text{O}_2\text{NO}_2$  downwind of biomass burning events as confirmed by large concentrations of peroxyacetyl nitrate and

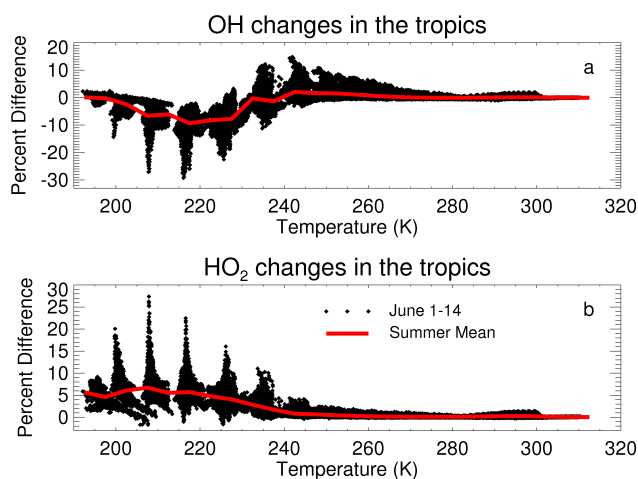
CO in these plumes (not shown). These spikes appear at regular intervals due to the decreased vertical resolution of the model in the upper troposphere. Each group of points are the results from a different vertical level of the model. In these particular biomass burning events,  $\text{CH}_3\text{O}_2\text{NO}_2$  chemistry results in maximum changes of  $\sim 20$ – $40\%$  (25–70 pptv) less  $\text{NO}_x$  (Fig. 6a),  $\sim 2$ – $4\%$  (1.5–2.6 ppbv) less ozone (Fig. 6b),  $\sim 20$ – $35\%$  (0.7–1.2 pptv) less  $\text{N}_2\text{O}_5$  (Fig. 6c),  $\sim 7$ – $20\%$  (1.5–6 pptv) less  $\text{HO}_2\text{NO}_2$  (Fig. 6d),  $\sim 7$ – $14\%$  (15–40 pptv) less  $\text{HNO}_3$  (Fig. 6e), and  $\sim 30$ – $75\%$  (20–60 pptv) more methyl hydrogen peroxide (Fig. 6f) as compared to the base case. As in the arctic, changes in methyl hydrogen peroxide are due to a combination of increased chemical production and increased lifetime in the MPN case compared to the base case. In the biomass burning plumes chemical production is up to  $\sim 90\%$  faster in the MPN case and the lifetime is  $\sim 29\%$  longer. Additionally, the MPN case has approximately 14–28% less OH (Fig. 7a) and 10–25% more  $\text{HO}_2$  (Fig. 7b) in these plumes than in the base case.

## 5 Implications

Through sequestration of  $\text{NO}_x$ ,  $\text{CH}_3\text{O}_2\text{NO}_2$  will directly affect the  $\text{NO}_x$  budget of the upper troposphere. Since lightning emits  $\text{NO}_x$  directly into the upper troposphere, these emissions will result in proportionally more  $\text{CH}_3\text{O}_2\text{NO}_2$  production than surface  $\text{NO}_x$  sources. Recently, several studies have attempted to constrain the lightning  $\text{NO}_x$  source by



**Fig. 6.** Differences between the GEOS-Chem base case and MPN case ( $((\text{MPN-BASE})/\text{BASE}) \times 100$ ) over the tropics versus temperature for (a)  $\text{NO}_x$ , (b) ozone, (c)  $\text{N}_2\text{O}_5$ , (d)  $\text{HO}_2\text{NO}_2$ , (e)  $\text{HNO}_3$ , and (f) methyl hydrogen peroxide. The individual points are the 24 h average value of 1–14 June 2008. The red line is the summer mean concentration. The regular temperature intervals at low temperatures are a result of decreasing vertical resolution in the model at increasing altitudes.

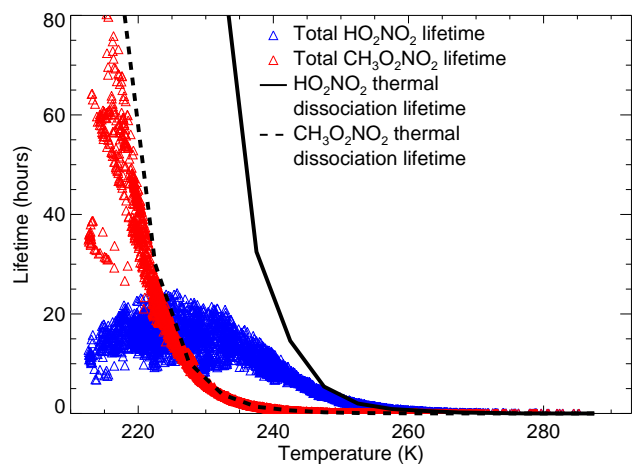


**Fig. 7.** Differences between the GEOS-Chem base case and MPN case ( $((\text{MPN-BASE})/\text{BASE}) \times 100$ ) over the tropics versus temperature for (a) OH and (b)  $\text{HO}_2$ . The individual points are the 24 h average value of 1–14 June 2008. The red line is the summer mean concentration. The regular temperature intervals at low temperatures are a result of decreasing vertical resolution in the model at increasing altitudes.

varying emissions in models and using top-down constraints from aircraft (e.g. Hudman et al., 2007) or satellite (e.g. Martin et al., 2007) measurements. It is possible that inclusion of  $\text{CH}_3\text{O}_2\text{NO}_2$  chemistry will necessitate an increase in these lightning  $\text{NO}_x$  estimates; however this effect will be sensitive to the altitude of lightning  $\text{NO}_x$  emissions. Over the tropics the  $\text{CH}_3\text{O}_2\text{NO}_2$  to  $\text{NO}_x$  ratio peaks at  $\sim 30\%$  between 11 and 12 km altitude and then decreases to  $\sim 15\%$  by  $\sim 9.9$  km and  $\sim 14$  km. Consequently, calculations of lightning  $\text{NO}_x$  emitted between 11 and 12 km will be most strongly affected by  $\text{CH}_3\text{O}_2\text{NO}_2$  chemistry.

The decrease in upper tropospheric  $\text{NO}_x$  from inclusion of  $\text{CH}_3\text{O}_2\text{NO}_2$  results in increases in  $\text{HO}_2$  and decreases in OH in the upper troposphere, thus increasing the  $\text{HO}_2$  to OH ratio. During the Intercontinental Chemical Transport Experiment-A (INTEX-A) Ren et al. (2008) found that the observed  $\text{HO}_2/\text{OH}$  ratio was larger than box-model predictions in the upper troposphere. Although the box-model used in Ren et al. (2008) contains  $\text{CH}_3\text{O}_2\text{NO}_2$  chemistry, it was constrained to measured  $\text{NO}_2$  concentrations. It is likely that these concentrations are measurements of  $\text{XNO}_2$ . We expect that the difference in the box model results constrained to  $\text{XNO}_2$  versus the results constrained to  $\text{NO}_2$  would be qualitatively similar to the changes observed between our base case and MPN case GEOS-Chem runs. The magnitude of the change in  $\text{HO}_2$  between the MPN and base case runs is significantly smaller than the





**Fig. 8.** Temperature dependence of CH<sub>3</sub>O<sub>2</sub>NO<sub>2</sub> and HO<sub>2</sub>NO<sub>2</sub> lifetimes for conditions sampled during ARCTAS. Symbols represent total lifetimes and solid lines are 5 K binned thermal lifetimes. IR photolysis for HO<sub>2</sub>NO<sub>2</sub> is estimated as  $1 \times 10^{-5} \text{ s}^{-1}$  ( $\sim 27.8 \text{ h}$ ).

measurement-model differences observed during INTEX-A by Ren et al. (2008). We conclude that CH<sub>3</sub>O<sub>2</sub>NO<sub>2</sub> interference in the NO<sub>2</sub> measurement during INTEX-NA may be responsible for part of the difference between measured and modeled HO<sub>x</sub> and NO<sub>x</sub> during INTEX-NA, but there are still unexplained measurement-model discrepancies.

It is also interesting to note that because both the reaction with OH and IR photolysis are negligible loss processes for CH<sub>3</sub>O<sub>2</sub>NO<sub>2</sub>, CH<sub>3</sub>O<sub>2</sub>NO<sub>2</sub> has a longer lifetime than HO<sub>2</sub>NO<sub>2</sub> at temperatures below  $\sim 225 \text{ K}$  (symbols in Fig. 8) under daytime conditions. Therefore, in the coldest conditions of the upper troposphere during the day, CH<sub>3</sub>O<sub>2</sub>NO<sub>2</sub> is a more effective reservoir of NO<sub>x</sub> and HO<sub>x</sub> than HO<sub>2</sub>NO<sub>2</sub>. However, at night the lifetimes of CH<sub>3</sub>O<sub>2</sub>NO<sub>2</sub> and HO<sub>2</sub>NO<sub>2</sub> will be controlled only by thermal decomposition (lines in Fig. 8) and CH<sub>3</sub>O<sub>2</sub>NO<sub>2</sub> will have a much shorter lifetime. For instance, assuming nine hours of darkness at 225 K, 40 % of CH<sub>3</sub>O<sub>2</sub>NO<sub>2</sub> will decompose, releasing CH<sub>3</sub>O<sub>2</sub> and NO<sub>2</sub>, whereas HO<sub>2</sub>NO<sub>2</sub> will remain intact. Thus, these two species will have different diurnal effects on the radical concentrations.

By using reduced pressures, shorter residence times (e.g. Bradshaw et al., 1999), or some combination thereof, it is possible for future inlet designs for upper tropospheric NO<sub>2</sub> measurements to minimize the interference of CH<sub>3</sub>O<sub>2</sub>NO<sub>2</sub>. In the TD-LIF system this would enable detection of CH<sub>3</sub>O<sub>2</sub>NO<sub>2</sub> solely in the peroxy nitrates channel. Although TD-LIF provides the sum measurement of all peroxy nitrate species, an indirect measurement of CH<sub>3</sub>O<sub>2</sub>NO<sub>2</sub> would be possible using the difference between the TD-LIF signal and speciated peroxy acetyl nitrates and pernitric acid measurements.

## 6 Conclusions

Measurements from ARCTAS indicate that the thermally unstable CH<sub>3</sub>O<sub>2</sub>NO<sub>2</sub> dissociates in the inlet of NO<sub>2</sub> instruments resulting in upper tropospheric measurements of NO<sub>2</sub> that are better described as thermally labile nitrogen (XNO<sub>2</sub>). Using the measurements of XNO<sub>2</sub> during ARCTAS we show that in the coldest conditions sampled, CH<sub>3</sub>O<sub>2</sub>NO<sub>2</sub> is present at concentrations approximately equal to or greater than NO<sub>2</sub>. Inclusion of CH<sub>3</sub>O<sub>2</sub>NO<sub>2</sub> chemistry in the GEOS-Chem model results in changes in concentrations of NO<sub>x</sub> and HO<sub>x</sub> and their reservoirs (such as N<sub>2</sub>O<sub>5</sub>, HNO<sub>3</sub>, and methyl hydrogen peroxide). The magnitude of the changes vary by season and region, however our results indicate that the addition of CH<sub>3</sub>O<sub>2</sub>NO<sub>2</sub> chemistry to GEOS-Chem results in significant changes whenever the temperature is below 240 K. These changes affect the calculated production and loss rates of NO<sub>x</sub> and HO<sub>x</sub>, the upper tropospheric HO<sub>2</sub> to OH ratio and the spatial distribution of NO<sub>x</sub> and HO<sub>x</sub> reservoirs. As shown by the results from the North American Arctic, addition of CH<sub>3</sub>O<sub>2</sub>NO<sub>2</sub> chemistry to models results in changes to the seasonal cycles of NO<sub>y</sub> and HO<sub>y</sub> species, particularly in the increase in N<sub>2</sub>O<sub>5</sub> and HO<sub>2</sub>NO<sub>2</sub> between 230 K and 260 K. The results from the tropics also indicate that CH<sub>3</sub>O<sub>2</sub>NO<sub>2</sub> plays an important role in the evolution of biomass burning plumes that are lofted to high altitudes. By sequestering both CH<sub>3</sub>O<sub>2</sub> and NO<sub>2</sub>, CH<sub>3</sub>O<sub>2</sub>NO<sub>2</sub> changes the chemical evolution and ozone production potential of these plumes.

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