Nitrogen oxide chemistry in an urban plume: investigation of the chemistry of peroxo and multifunctional organic nitrates with a Lagrangian model

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Abstract

Air quality in the outflow from urban centers affects millions of people, as well as, natural and managed ecosystems downwind. In locations where there are large sources of biogenic VOCs downwind of urban centers, the outflow is characterized by a high VOC reactivity due to biogenic emissions and low NO\textsubscript{x}. However most field and chamber studies have focused on limiting cases of high NO\textsubscript{x} or of near zero NO\textsubscript{x}. Recent measurements of a wide suite of VOCs, O\textsubscript{3} and meteorological parameters at several locations within the Sacramento urban plume have provided a detailed benchmark for testing our understanding of chemistry in a plume transitioning from high NO\textsubscript{x} to low NO\textsubscript{x} and high VOC reactivity. As an additional simplification, the strong mountain valley circulation in the region makes this urban plume a physical realization of a nearly idealized Lagrangian plume. Here, we describe a model of this plume. We use a Lagrangian model representing chemistry based on the Master Chemical Mechanism (MCM) v3.1 along with mixing and deposition. We discuss the effects of entrainment of background air, the branching ratio for the production of isoprene nitrates and the effects of soil NO\textsubscript{x} emissions on the composition of the evolving plume. The model predicts that after 2–3 h of chemical processing only 45% of the peroxynitrates (ΣPNs) are PAN and that most (69%) RONO\textsubscript{2} are secondary alkyl nitrate products of the reaction of OH with RONO\textsubscript{2}. We find the model is more consistent with the observations if: a) the yield of ΣPNs from large and multi-functional aldehydes is close to zero; and b) the reaction between OH and RONO\textsubscript{2} produces multifunctional nitrates as opposed to either HNO\textsubscript{3} or NO\textsubscript{2} as is typical in most currently adopted reaction mechanisms. Model results also show that adding NO\textsubscript{x} emissions throughout the transect increases the available NO\textsubscript{x} in the downwind regions, but modeled ozone concentrations were little affected by the increased NO\textsubscript{x}.
1 Introduction

Ozone is produced by a series of catalytic reactions involving the oxidation of organic molecules in the presence of NO\textsubscript{x} (NO\textsubscript{x} ≡ NO+NO\textsubscript{2}) and sunlight (Haagen-Smit, 1952). While the basic chemistry of the catalytic cycles is well known, demonstrating that we have an accurate and complete understanding of the chemistry, especially the role of various chain termination steps, remains elusive and challenging because direct simultaneous measurements of key radical species and the molecules that are formed during chain termination reactions are not routine and in some cases not yet possible. An additional limitation is that the most extensive tests of our understanding of ozone production chemistry using ambient measurements have focused on limiting cases of high NO\textsubscript{x} or of near zero NO\textsubscript{x}.

Here we take advantage of measurements of a wide suite of VOCs, O\textsubscript{3} and meteorological parameters at several locations within the Sacramento urban plume that provide a detailed benchmark for testing our understanding of chemistry in a plume transitioning from high NO\textsubscript{x} to low NO\textsubscript{x} under conditions of near constant and high VOC reactivity. As an additional simplification, the strong mountain valley circulation in the region makes this urban plume a physical realization of a nearly idealized Lagrangian plume. We evaluate a Lagrangian model representing chemistry based on the Master Chemical Mechanism (MCM) v3.1 along with mixing and deposition in this plume. The model is compared to observations of NO\textsubscript{x} and its oxidation products, including total peroxynitrates (ΣPNs), total alkyl nitrates (ΣANs) and HNO\textsubscript{3}. We begin (Sect. 2) with a brief review of our understanding of the transport and chemistry of the Sacramento plume, followed by a description of the model (Sect. 3). The model and observations are compared in Sect. 4, along with descriptions of the constraints on some of the more uncertain parameters in the model. In Sect. 5 we consider the sensitivity of the model to soil NO\textsubscript{x} emissions and provide estimates for N deposition along the model transect. We conclude with suggested improvements to the representation of NO\textsubscript{x} oxidation chemistry in the current generation of photochemical mechanisms.
2 The Sacramento urban plume

The western slope of the Sierra Nevada experiences extremely regular wind patterns, especially during the summer. Figure 1 shows the study region and provides an overview of the flow patterns that affect it. Daytime heating causes upslope flow that draws air from California’s Central Valley eastward into the higher elevations of the Sierra Nevada Mountains. In the evening, cooling in the valley causes a flow reversal and the air drains from higher elevations back toward the valley floor. As a result, daytime chemistry is approximately described as a flow reactor with dilution as evidenced in the diurnal patterns observed in many primary and secondary chemicals observed in the region (van Ooy and Carroll, 1995; Baker et al., 1999; Lamanna and Goldstein, 1999; Dillon et al., 2002; Schade et al., 2002; Day et al., 2003; Cleary et al., 2005, 2007; Murphy et al., 2006a, b, 2007; Day et al., 2008, 2009).

The chemical composition of the Sacramento urban plume is especially well characterized as a result of these observations which include regional ozone studies, many summers and several complete annual cycles of measurements at a Ponderosa Pine plantation near the University of California-Blodgett Forest Research Station (UC-BFRS), short-term studies at Granite Bay (GB), and Big Hill, and observations from aircraft. These observations have been used to describe the behavior of anthropogenic and biogenic species including VOC, nitrogen oxides and O$_3$ and they have been used to gain insight of the photochemistry in the plume in the Sacramento area and in the downwind Mountain Counties (Baker et al., 1999; Lamanna and Goldstein, 1999; Schade and Goldstein, 2001; Dreyfus et al., 2002; Kurpius et al., 2002a; Schade et al., 2002; Day et al., 2003; Cleary et al., 2005, 2007; Murphy et al., 2006a, b, 2007; Day et al., 2008, 2009).

The most complete overview of factors affecting the photochemistry in the region is presented by Murphy et al. (2006b) who analyzed observations of day-of-week patterns and diurnal profiles of odd oxygen (O$_x$≡O$_3$+NO$_2$), ozone and its precursors. They report that the sites in the Sacramento Valley Air Quality District (Sacramento itself and
its closest suburbs; see Fig. 1) are more likely to exceed the national 8-h ozone standard (75 ppb) on the weekend, while sites in the Mountain Counties (regions downwind of the city) are more likely to exceed the national ozone standard on the weekdays. Murphy et al. (2006b, 2007) separate the effects of a) titration by NO, b) odd-oxygen production and c) carryover of O\textsubscript{x} and O\textsubscript{x} precursors from the previous day. They show that the transition between NO\textsubscript{x}-limited and NO\textsubscript{x}-saturated photochemical regimes occurs near or just downwind of the suburban boundary of the Sacramento metropolitan area and that carryover from the previous day plays an important role in O\textsubscript{x} concentrations in the region. These are results with important policy implications as they suggest that further NO\textsubscript{x} reductions in the region will be immediately effective at reducing ozone in the suburbs and provide a quantitative estimate for how much additional NO\textsubscript{x} reduction is required (50%) to reduce ozone in the center of the city. Murphy et al. (2006b) also use isoprene observations as a diagnostic of OH concentrations that supports the conclusions of their analysis. They show that lower NO\textsubscript{x} on the weekend translates to lower OH concentrations in the rural areas and to higher OH near the urban core confirming that NO\textsubscript{x} has a direct effect on oxidation rates (and ozone production rates) in the plume.

3 A Lagrangian – MCM model of the Sacramento plume

We build on a previous analysis by Dillon et al. (2002) who developed a Lagrangian model incorporating oxidation and mixing and then used observations of VOCs for which the only source was assumed to be the Sacramento region to constrain the model. In that research, a nonlinear least square optimization of the decrease in VOC from the initial urban value to that observed at UC-BFRS resulted in determination of the average OH concentration and the average dilution rate during the transit. At the peak impact of the Sacramento plume at UC-BFRS, the derived parameters were a dilution rate of 0.23±0.07 h\textsuperscript{-1} and an OH concentration of 11±5×10\textsuperscript{6} molecules cm\textsuperscript{-3}.

We have investigated the performance of this model in more detail, finding that
these two parameters are not as cleanly separated by the original VOC data set as initially believed and that they are anti-correlated, thus a low value for the OH concentration requires high mixing rate and vice versa. Schade et al. (2002) derived a similar OH of 9–13×10^6 molecules cm^{-3}, based on the observed diurnal cycle of MTBE and its ratio to 2-methyl-butane. Dreyfus et al. (2002) derived a value of 9 (±4)×10^6 molecules cm^{-3} based on the observed daytime methylvinyl ketone to methacrolein (MVK/MACR) ratio. These two studies do not explicitly treat dilution, thus making the implicit assumption that dilution affects the pairs of species (MTBE and 2-methyl-butane or MVK and MACR) equally. Nevertheless, they do arrive at essentially the same value for OH as Dillon et al. (2002). The average OH experienced during the plume transport, is of course not the OH at any one location. We know that the decreases in NO_x that occur during transport result first in an OH increase and then an OH decrease (Murphy et al., 2006b). This fact makes it desirable to develop a model capable of describing the changing OH field throughout the plume evolution instead of an effective concentration. We do that by incorporating a full photochemical model into the Lagrangian framework outlined by Dillon et al. (2002). This model represents mixing, photochemistry, and dry deposition as occurring in a box that is transported from Granite Bay, at the edge of the urban center, to UC-BFRS at a rate set by the local winds. Among the advantages of this model are the ability to easily tune the model parameters or to fit them in a non-linear least squares sense, and the ability to use a model with as complete a representation of the chemistry as desired.

The model is formulated as follows. The change in concentration of a compound X with time is described by Eq. (1):

\[
d[X]/dt = P_x - L_x + E_x - D_x - M_x
\]  

(1)

where \( P \) is photochemical production, \( L \) is photochemical loss, \( E \) represents emissions, \( D \) is deposition, and \( M \) represents mixing and entrainment of background air. The model uses Eq. (1) to compute the time-dependent chemical evolution of "\( n \)" molecules \( X_1 - X_n \) in the air parcel.
The chemical mechanism representing both the production ($P_x$) and loss ($L_x$) terms of Eq. (1) (see Appendix 1 for the detailed reaction set) includes 370 reactions, 170 specific chemicals and 7 lumped species representing the oxidation of VOCs by OH and O$_3$ in the presence of NO$_x$ as described by the Master Chemical Mechanism v3.1 (MCM) (Bloss et al., 2005a, b). Photolysis rate coefficients are taken from the TUV model (Madronich, 1987; Madronich and Flocke, 1998), with an ozone column of 300 DU and an aerosol vertical optical depth of 0.235, and from MCM (Bloss et al., 2005a, b) and vary according to solar zenith angle. Exception to strict adherence to MCM protocols are as follows.

1) Oxidation by the nitrate radical is not included because its concentration is assumed to be small during the daytime (12:00–17:00 LT) due to its short photolytic lifetime ($\tau = 5$ s at noon).

2) Rate constants are taken from Sander et al. (2006) when available; otherwise rate constants are taken from MCM (Bloss et al., 2005a, b) (e.g. IsopO$_2$+RO$_2$).

3) Isoprene and MBO are treated according to the MCM through the third generation oxidation products. After this point the products are lumped into a generic aldehyde species.

4) Monoterpene oxidation, represented by the oxidation of $\alpha$-pinene, is treated according to Atkinson and Arey (2003).

5) The oxidation mechanism for isoprene nitrates allows the products of this reaction to be either a more highly functionalized alkyl nitrate (hydroxy alkyl nitrate) or NO$_2$ (Farmer and Cohen, 2008; Paulot et al., 2009; Perring et al., 2009). The MCM treats these reactions as producing NO$_2$ with 100% efficiency. In our reference model, isoprene nitrates (INs) are oxidized at the double bond instead of the nitrate group, to give a lumped class of more functionalized hydroxy alkyl nitrates at unit yield. Upon further oxidation (with $\tau_{OH} \sim 50$ h), this secondary class of isoprene nitrates releases NO$_2$. Oxidation of all non-isoprene ANs are treated as prescribed by MCM.

6) Alkoxy radicals are assumed to react instantly with O$_2$.

The resulting mechanism includes numerous individual aldehydes, ketones, organic
acids, alcohols and peroxides. It includes 12 specific and 1 lumped alkyl or multifunc-
tional nitrate and 9 specific and 1 lumped peroxy acyl nitrate. It includes a lumped aldehyde and a lumped organic peroxide.

HO\textsubscript{x} species are calculated at each time step assuming they are in photostation-
ary state with the NO\textsubscript{x}, VOC and sunlight. Important sources of HO\textsubscript{x} in the model include the reaction of O\textsuperscript{1}D with water, photolysis of CH\textsubscript{2}O to produce HO\textsubscript{2}, photolysis of methylglyoxal and reactions of O\textsubscript{3} with VOCs to produce OH, HO\textsubscript{2} and RO\textsubscript{2} species. There are a total of 14 specific RO\textsubscript{2} and 10 specific RCOO\textsubscript{2} and lumped values repre-
senting other RO\textsubscript{2} and other RCOO\textsubscript{2} radicals.

Modeled emissions of biogenic VOCs including isoprene, MBO and terpenes vary with temperature, PAR and land cover based on Steiner et al. (2006). Terpenes are assumed to be emitted in the form of \(\alpha\)-pinene. Anthropogenic emissions are assumed to be zero. Biogenic NO\textsubscript{x} emissions are estimated from measured fluxes of soil NO\textsubscript{x} in the oak forests of the Sierra Nevada foothills (Herman et al., 2003). A consistent emission flux of 10 ppt m s\textsuperscript{-1} (5.7 ng (N) m\textsuperscript{-2} s\textsuperscript{-1}) is applied to the entire transect.

Peroxy acyl nitrates, alkyl and multifunctional nitrates and HNO\textsubscript{3} are assumed to have deposition velocities (\(V_{dep}\)) of 1.1 cm/s, 2.7 cm/s and 3.4 cm/s, respectively (Farmer and Cohen, 2008). Deposition of O\textsubscript{3} is included with a \(V_{dep}\) of 0.8 cm/s (Kurpius et al., 2002b). Deposition of other species is neglected.

We use the boundary layer averaged temperature which we estimate based on ob-
served surface temperatures at Granite Bay and at UC-BFRS and the environmental lapse rate (6.5\textdegree C/km); the temperature is varied during the plume transit. The bound-
ary layer height is assumed to be 800 m above the surface at all points along the transect.

Calculations of the chemical evolution of the plume depends on accurate estimation of mixing/dilution rates as this is the single most important factor affecting concentra-
tions. Mixing is assumed to be of the form:

\[
d[X]/dt = -k_d ([X] - [X]_{bg})
\]
where \( k_d \) represents the dilution rate and the quantity \([X]_{bg}\) refers to the concentration of the species X in the background air that the plume is mixing with. In this formulation, we believe the calculation is most representative of the center line of the plume and that the single mixing parameter is likely more representative of vertical than horizontal mixing.

At characteristic wind speeds, air masses passing over Granite Bay at 12:00 LT represent the initial conditions for air masses that reach the UC-BFRS at 17:00 LT. We chose this temporal window both to coincide with peak ozone concentrations and other urban influences at UC-BFRS at the end of the day, and to minimize uncertainty in the initial conditions associated with a dynamically growing planetary boundary layer. Planetary boundary layer growth is a strong and obvious feature in the measurements between 06:00 LT and 10:00 LT.

The model is initialized with the noontime (11:00 LT to 13:00 LT median) observations of NO\(_2\), total peroxynitrates (ΣPNs), total alkyl and multifunctional nitrates (ΣANs), HNO\(_3\), a wide suite of anthropogenic and biogenic VOCs and O\(_3\) obtained at Granite Bay, CA (38° N 44.23′, 121° W 12.01′, 277 m a.s.l. during the period of 19 July–15 September 2001. This site is located 30 km north-east of Sacramento, CA, at the eastern edge of the suburban sprawl. These measurements and methods are described in detail by Cleary et al. (2005) and Millet et al. (2005). In this paper, we use data from Tuesdays through Fridays because differences in weekend emission patterns result in differences in chemistry (Murphy et al., 2006b; Murphy et al., 2007). Initial CO concentrations are based on measurements by the California Air Resources Board (CARB, 2009) at the North Highlands site located between one and two hours upwind of Granite Bay (∼16 km) and methane is set at 1.85 ppm. A 3-h spin-up period initialized with 09:00 LT observations is used to set the concentration of species not measured and to obtain a speciated composition of ΣPNs and ΣANs. During the spin-up period, emissions of all measured species are tuned so that final values at noon match the observations. Table 1 shows a list of the input parameters. Following this initialization, the plume is then propagated forward in time and space to represent the
We determine the constant $k_d$ by updating the analysis of Dillon et al. (2002) and using VOCs with lifetimes with respect to $3 \times 10^6$ molecules cm$^{-3}$ of OH ranging from 1 to 6.5 d. Using a single value for OH, we find an average $[\text{OH}]=8\pm3 \times 10^6$ molecules cm$^{-3}$ and $k_d=0.24\pm0.06$ h$^{-1}$. These are similar to those obtained by Dillon et al. (2002) ($\text{OH}=11\pm5 \times 10^6$ molecules cm$^{-3}; k_d=0.23\pm0.07$ h$^{-1}$). In the current analysis, the two parameters are only weakly anti-correlated. The largest uncertainty in determining these parameters is knowledge of the background concentration. We use estimates of free tropospheric (above the planetary boundary layer) values based on measurements made directly along this transect on the return flight from the NASA TC4 experiment in 2007.

As noted above, an advantage of the model structure we have developed is that we are not forced to use a single value of OH. If we allow OH to vary during transport in response to changes in VOC reactivity, NO$_x$, peroxy radical concentrations, and other relevant production and loss terms, the optimization leads to $k_d=0.31$ (±0.026) h$^{-1}$ and an average OH of $5.0 \times 10^6$ molecules cm$^{-3}$. This value for $k_d$ is used in the analysis described below. Additional details of the determination of OH and $k_d$ are described in Appendices B and C.

4 Analysis of nitrogen oxide partitioning

In this section we provide an analysis of the model output with respect to nitrogen oxide partitioning using observations of NO$_x$, ΣPNs, ΣANs, and HNO$_3$ at UC-BFRS. We discuss the sensitivity of the model results to various physical parameters such as $k_d$, soil NO$_x$ emissions, and deposition rates. Further, we explore the impact of some of the more uncertain parameters in the chemical mechanisms for acyl peroxy nitrates and hydroxy alkyl nitrates. Finally, we summarize our recommendations for a revised chemical mechanism that is consistent with recent research on isoprene
nitrates (Paulot et al., 2009; Perring et al., 2009) and PAN (LaFranchi et al., 2009; Wolfe et al., 2009).

### 4.1 Total nitrogen oxides

Comparison of the *Reference* model to observed nitrogen oxide concentrations at UC-BFRS is summarized in column 1 of Table 2 and shown graphically in Fig. 2. Figure 3 is a plot of the individual components of NO\textsubscript{y} over time as the plume travels from Granite Bay to UC-BFRS. ΣNO\textsubscript{y} is initialized at the observed value of 13.18 ppb and is observed at to be 3.38 ppb at UC-BFRS. The predicted mixing ratio is 2.95 ppb, 15% lower than observed. Most of this decrease (77%) in ΣNO\textsubscript{y} over the transect is calculated to be due to entrainment with the remaining 23% due to deposition. Perfect agreement between the model and observations could be achieved by increasing the initial NO\textsubscript{y} from 13.18 ppb to 16 ppb, increasing the background NO\textsubscript{y} by a factor of 1.75 from 0.825 ppb to 1.4 ppb, decreasing the mixing rate by 13% (0.31 h\textsuperscript{-1} to 0.27 h\textsuperscript{-1}), or decreasing the ratio of the deposition velocities (V\textsubscript{dep}) to the planetary boundary layer (PBL) height by 45%. The changes needed in initial ΣNO\textsubscript{y} and in ΣNO\textsubscript{y} background are both larger than what the observations suggest is a possible range. The change in the ratio of V\textsubscript{dep} to PBL height is also unreasonably large. A 13% decrease in the dilution rate is just outside the range of uncertainty of the parameter (0.31(±0.026) h\textsuperscript{-1}) estimated from a fit to the 10 VOCs described above and in Appendix B. This indicates that some combination of errors is the cause of the difference between the model and observations.

### 4.2 NO\textsubscript{x}

The initial ΣNO\textsubscript{y} at Granite Bay is 60% NO\textsubscript{x}. As the plume evolves, NO\textsubscript{x} is diluted by entrainment of cleaner air, is oxidized, and is produced by decomposition of PNs and oxidation of ΣANs and HNO\textsubscript{3}. Mixing of background air accounts for 50% of the reduction in NO\textsubscript{x} observed in the model and 26% is due to oxidation of NO\textsubscript{2} to HNO\textsubscript{3}.

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The remaining decrease in NO\textsubscript{x} is the loss by oxidation to ΣANs (6%) and ΣPNs (18%), less the amount recycled from these compounds back to NO\textsubscript{x}. The model predicts that NO\textsubscript{x} at UC-BFRS is 734 ppt; this is an underestimate of 18%, about the same as the 15% underestimation of total NO\textsubscript{y}. The model predicts that 25% of ΣNO\textsubscript{y} at UC-BFRS is in the form of NO\textsubscript{x}, in good agreement with observations (26%), indicating that the model does a reasonable job of reproducing the partitioning between NO\textsubscript{x} and NO\textsubscript{z} (NO\textsubscript{z} = ΣPNs + ΣANs + HNO\textsubscript{3}).

4.3 ΣPNs

Peroxy acyl nitrates are formed through the reaction of peroxy acyl radicals with NO\textsubscript{2}. ΣPNs are a unique in the class of nitrogen oxides because they thermally dissociate to release NO\textsubscript{x}. Therefore, at the moderately high temperatures characteristic of the summer months in the region studied, ΣPNs are a source of NO\textsubscript{x}. The observations of peroxy acyl nitrates at Granite Bay and UC-BFRS account for the sum of all the species of the form RO\textsubscript{2}NO\textsubscript{2}, as discussed by Cleary et al. (2007) and Day et al. (2002). Figure 4a shows ΣPNs and its components along the transect in the Reference model.

We calculate concentrations of 9 speciated peroxy acyl nitrates including PAN and MPAN as well as a lumped peroxy acyl nitrate. After the initial 3-h spin up time, we calculate the initial ΣPNs to be 54% PAN, 11% MPAN, and 10% other speciated PNs with the remaining 25% a lumped PN. Cleary et al. (2007) estimate the partitioning of ΣPNs at Granite Bay based on measurements and estimates of aldehydes in the region. They calculate the ΣPNs to be a mixture of 70% PAN, 10% PPN, 3% MPAN with the remaining 17% other C\textsubscript{4}-C\textsubscript{9}PNs. The differences point to a variety of possible errors in VOC oxidation chemistry of MCM and the resulting aldehyde estimates at Granite Bay.

The components of ΣPNs calculated at UC-BFRS are 45% PAN, 39% lumped PNs, 7% MPAN, 6% 2-hydroxy-2-methyl peroxypropionyl nitrate (C\textsubscript{4}PAN\textsubscript{5}) which is a peroxy acyl nitrate species formed via the oxidation of MBO and 3% distributed among the 6 remaining speciated peroxy acyl nitrates. Glycoaldehyde, an oxidation product of both
MBO and isoprene, is a major source of non-speciated PNs in the model. Another significant source of these lumped PNs is the unspeciated class of aldehydes, which are the sum of all untracked of anthropogenic VOCs, including many 1st generation oxidation products of AVOCs. These predictions of speciation are inconsistent with recent observations at UC-BFRS (LaFranchi et al., 2009; Wolfe et al., 2009) and with analysis of several previous data sets where ΣPNs and individual PNs were measured (Wooldridge et al., 2009). In each of these studies, PAN is typically 80–90% of ΣPNs, with the remaining 10–20% being comprised of MPAN and PPN. PPN is not tracked in the model due to a lack of observations of propanal; we expect that inclusion of PPN would add 5–10% to the ΣPNs budget in this model (LaFranchi et al., 2009). Using an estimated propanal concentration along the transect, we find that when PPN is 10% of ΣPNs, the ΣPNs/NOx ratio increases by 10%.

The modeled ΣPNs/NOx ratio is 1.052, close to the observed value of 1.09. The ΣPNs/NOy ratio is 0.26, slightly lower than the observed value of 0.28. There are significant discrepancies, however, between the ΣPNs composition in the model and that observed at UC-BFRS. Specifically, PAN is too small relative to ΣPNs, and the lumped PNs are too large. Since the ΣPNs/NOx ratio is in relative agreement with observations, despite these discrepancies, it is likely that there are two or more canceling errors in the model resulting in: a) an underestimate of the peroxy acetyl (PA) radical abundance, leading to an underestimate of PAN, and b) a compensating overestimate of the stability of the unspeciated class of PNs or the abundance of its precursors, leading to unrealistically high concentrations of these species as a fraction of ΣPNs.

An underestimate of PA radical sources is common in many previous studies where isoprene chemistry is important (Roberts et al., 2001; Roberts et al., 2006; Cleary et al., 2007). However, recent observations of PAN at UC-BFRS have shown that the total PA radical source can be quantified by including production from acetaldehyde, methylvinyl ketone (MVK), methyl glyoxal, methacrolein, and biacetyl (LaFranchi et al., 2009). The only molecule that is not tracked in the model is biacetyl, which photolyzes to give 2 PA radicals and was found to be responsible for 15–25% of the total PA
radical source at UC-BFRS (LaFranchi et al., 2009). An additional source of error, however, is that MVK (Dreyfus et al., 2002) and acetaldehyde (Schade and Goldstein, 2001) at UC-BFRS are underestimated in the model by 10% and 100%, respectively. Artificially adding sources of acetaldehyde, biacetyl, and MVK along the transect to match observations of these oVOCs at UC-BFRS increases the PA radical production rate by nearly a factor of 2.

An overestimate of the abundance of lumped PNs in the model is not surprising, given that a wide variety of oVOCs of varying chain-length and functionality are treated identically in their ability to form PNs. It is likely that many of these aldehydes do not form PNs in the atmosphere. For example, Magneron et al. (2005) found no evidence for PN formation in an experimental study of the oxidation of glycoaldehyde, an important component of lumped PNs in the MCM chemistry. Additionally, Carrasco, et al. (2006) studied the fate of 2-hydroxy-2-methylpropanal (C4PAN5, in Fig. 3) using the EUPHORE outdoor simulation chamber and observed a 100% apparent yield for acetone production following reaction with OH, whether NO\(_x\) was present or not, apparently indicating the corresponding PN is not formed.

To incorporate the above discussion into the model, a model scenario (PNs_1 in Table 2) was run in which the production of unspeciated PNs is set to zero and the PA production rate is doubled (by artificially increasing acetaldehyde and biacetyl sources). Figure 4b shows the PNs composition along the transect in this model scenario. Relative to the Reference case, there is a significant increase in the fraction of \(\Sigma\)PNs that are PAN and a net decrease in the \(\Sigma\)PNs/NO\(_x\) ratio. The model output in this case underestimates the observed \(\Sigma\)PNs/NO\(_x\) ratio by 22%, indicating that a further increase in the PA radical source at some point along the transect is required. Not accounting for PPN production in this model scenario could account for 25–50% of the 22% underestimate in the \(\Sigma\)PNs/NO\(_x\) ratio.
4.4 ΣANs

Observations of total alkyl and multifunctional nitrates at Granite Bay and UC-BFRS have been described by Cleary et al. (2005) and Day et al. (2003). The ΣANs composition predicted at UC-BFRS in the Reference model is 68% a lumped hydroxy alkyl nitrate that is the product of the reaction of isoprene-derived RONO₂ (INs) with OH, 11% isoprene nitrates, 17% alkyl nitrates produced from MBO oxidation, 3% primary Σnon-speciated ANs and 1% the sum of the 4 other speciated alkyl nitrates (MVKANO₃, C₅₈NO₃, CH₃NO₃, and AromaticNO₃) that are tracked in the model. Figure 5 shows the time evolution of these fractions of ΣANs in the reference model along with the ΣANs observed at UC-BFRS. Isoprene nitrates and their oxidation products comprise a large fraction of ΣANs in the model. This detailed calculation supports previous assertions and calculations that ΣANs are a complex mixture (Day et al., 2003) and that they are a major NOₓ reservoir. Further, the calculation indicates that the primary ANs are a small fraction of the total, even in regions with a very strong influence from biogenics.

The parameters used in predicting ANs are among the more uncertain ones in the model. Alkyl nitrates are produced via the reaction of RO₂ with NO

\[ \text{RO}_2 + \text{NO} \rightarrow \text{RO} + \text{NO}_2 \]  
(R1a)

\[ \text{RO}_2 + \text{NO} \rightarrow \text{AN} \]  
(R1b)

where \( \alpha \), known as the branching ratio, is the fraction of the time an AN is produced instead of an NO₂ molecule. For many molecules the branching ratio is not well known. Oxidation products of ANs are even less well understood. Reactions of ANs can lead to a multifunctional compound that retains the –ONO₂ functional group (R2a) or release NO₂ (R2b).

\[ \text{AN} + \text{OH} \rightarrow \text{ANOH} \]  
(R2a)

\[ \text{AN} + \text{OH} \rightarrow \text{oVOC} + \text{NO}_2 \]  
(R2b)
Laboratory measurements of $\alpha$ for isoprene span a range from 4.4% to 15% (Tuazon and Atkinson, 1990; Chen et al., 1998; Chuong and Stevens, 2002; Sprengnether et al., 2002) with more recent values between 8% and 12% (Patchen et al., 2007; Paulot et al., 2009). In MCM, as well as in our reference model, the average branching ratio represented by the 4 isoprene nitrates isomers is 10.8%.

The effects of Reaction (R2) and the role of isoprene nitrates have been the subject of several recent manuscripts (Horowitz et al., 2007; Farmer and Cohen, 2008; Ito et al., 2009; Perring et al., 2009). Analyses of field data have resulted in estimates for combined parameters reflecting $\alpha$ for isoprene and the relative yield of ANOH in Reaction (R2) (via R2a). These variables affect the NO$_x$ budget and production of ozone on regional and global scales (Ito et al., 2009). Horowitz et al. (2007) recommended $\alpha=4\%$ as a best fit to $\Sigma$AN data with 60% of $\Sigma$ANs reacting via path 2a and 40% via 2b. Perring et al. (2009) compared field observations of the $\Sigma$ANs and CH$_2$O correlation and found a set of $\alpha$’s, lifetimes to OH, and ANOH yields (R2a) (4.4%, 16 h, and 97%; 8%, 2.5 h, and 79%; and 12%, 95 min, and 67%) that were each consistent with observations. Previous analysis by Farmer and Cohen (2008) at UC-BFRS suggested that 70–94% of the products of R2 are ANOH.

The slope of O$_3$ vs. ANs has been previously used to derive the effective branching ratio for the reaction of RO$_2$ with NO to produce $\Sigma$ANs (Day et al., 2003; Rosen et al., 2004; Cleary et al., 2005). This assumes that the production rates (P(O$_3$) and P($\Sigma$ANs)) are the only relevant processes that affect their respective concentrations. Using this method, Day et al. (2003) calculated an effective branching ratio of 2.5% at UC-BFRS and Cleary et al. (2005) calculated an effective branching ratio of 4.2% at Granite Bay. If we repeat these analyses for UC-BFRS, generating a range of model predictions by varying the temperature and initial NO$_x$ (details of these different model scenarios will be presented in a future manuscript), the slope of modeled O$_3$ to modeled $\Sigma$ANs is 83 and the calculated effective yield is 2.4%, approximately equal to the 2.5% inferred from observations by Day et al. (2003).

Despite the good agreement in the estimated effective yield, there are other pro-
cesses besides \( P(O_3) \) and \( P(\Sigma ANs) \) that affect the slope of this line which should be considered. In particular, the lifetime of \( \Sigma ANs \), a rather uncertain quantity due to uncertainties in the branching for Reaction (R4), will have a large effect on the \( O_3 \) vs. \( \Sigma ANs \) slope. The ratio of \( \Sigma ANs \) to \( NO_x \) is, perhaps, a better indicator of whether the balance between \( \Sigma ANs \) production and loss is modeled properly, since \( NO_x \) is both a precursor to and a potential reaction product of \( \Sigma ANs \).

The ratio of \( \Sigma ANs \) to \( NO_x \) (0.52) is underestimated in the Reference model by 13%. The underestimate of the \( \Sigma ANs/NO_x \) ratio indicates that the model does not accurately simulate the competition between \( \Sigma ANs \) production and its conversion back to \( NO_x \) in the atmosphere, resulting in too little \( \Sigma ANs \) production, too much \( NO_x \) recycling, or some combination of both. It should be noted that the \( \Sigma ANs/NO_x \) ratio in the model is relatively insensitive to changes made to the \( \Sigma PNs \) chemistry (as discussed in Sect. 4.3).

It is important, therefore, to probe the effects of changes to the \( \Sigma ANs \) production rate and the branching of Reaction (R2) independently in order to better evaluate the performance of the model and its sensitivities to each of these unknown parameters. Since isoprene is a significant portion of the VOC reactivity in the model, we can constrain the model with the findings of some recent studies on isoprene nitrate production and loss rates, thus testing our assumptions about the remaining fraction of \( \Sigma ANs \). In the following discussion, we study the effects of varying \( \alpha \) and the yield for Reaction (R2a) within the constraints laid out by Paulot et al. (2009) and Perring et al. (2009) and assess how these changes to the MCM chemistry scheme affect the \( \Sigma ANs/NO_x \) ratio in the model and how they compare to observations at UC-BFRS.

First the MCM \( \alpha \) values were scaled to 4.4% or 12% for isoprene nitrate production, while keeping the split between Reaction (R2a) and (R2b) as in the Reference case. The effect of changing \( \alpha \) for isoprene results in a \( \Sigma ANs \) concentration at UC-BFRS of 324 ppt in the 4.4% case (ANs_1 in Table 2) and 394 ppt in the 12% case (ANs_2), an overall change in \( \Sigma ANs \) of 20% between the two extremes. The change in the \( \Sigma ANs/NO_x \) in these two scenarios is also significant, varying from 0.43, when \( \alpha \) is
4.4%, to 0.54, when \( \alpha \) is 12%. The observed value is 0.59, suggesting an error in the model associated with the branching ratios of other alkyl nitrates or with the fate of the \( \Sigma \)ANs class.

Second, we examine the impact of introducing an NO\(_2\) recycling scheme to the model for isoprene nitrate oxidation that is consistent with Perring et al. (2009) and Paulot et al. (2009). In this scheme, the nitrate-peroxy radicals (IsopNO\(_3\)O\(_2\)), resulting from addition of OH to the isoprene nitrate double bond (R3), are tracked explicitly, in the same manner that other RO\(_2\) species are treated in the MCM. Paulot et al. (2009) found that when IsopNO\(_3\)O\(_2\) reacts with NO, 50% of the reactions lead to nitrate group retention (R4a) with the remaining 50% leading to recycling of NO\(_2\) (R4b). Reaction of IsopNO\(_3\)O\(_2\) with HO\(_2\) and RO\(_2\) (R4c) has yet to be studied experimentally; we assume here that this reaction always leads to retention of the nitrate group. The reaction series of (R3) and (R4) is analogous to (R2), as written above, however, it allows for a variable NO\(_2\) yield, depending on the [NO]/[HO\(_2\)+RO\(_2\)] ratio, which determines the branching between Reaction (R4a, b) and (R4c). When this chemistry is incorporated into the model, the NO\(_2\) yield ranges from 41–50% and is 46% on average across the transect.

\[
\begin{align*}
\text{IN + OH} & \rightarrow \text{IsopNO}_3\text{O}_2 & \text{(R3)} \\
\text{IsopNO}_3\text{O}_2 + \text{NO} & \rightarrow \text{ANOH} + \text{NO}_2 \quad \text{(yield = 50%)} & \text{(R4a)} \\
\text{IsopNO}_3\text{O}_2 + \text{NO} & \rightarrow \text{oVOC} + 2 \text{NO}_2 \quad \text{(yield = 50%)} & \text{(R4b)} \\
\text{IsopNO}_3\text{O}_2 + \text{HO}_2, \text{RO}_2 & \rightarrow \text{ANOH} & \text{(R4c)}
\end{align*}
\]

Paulot et al. (2009) also tracked a number of the second generation nitrate-containing products of Reaction (R4a). Since we do not treat the individual second generation nitrates explicitly, we vary the lifetime for this unspeciated pool of compounds so that the effective IN (both primary and secondary) lifetime equals 2.5 h, when \( \alpha=8\% \), and 95 min, when \( \alpha=12\% \). This allows for a direct comparison with two sets of NO\(_2\) yields.
and branching ratios identified by Perring et al. (2009) that are consistent with observations of ΣANs and CH₂O in the boundary layer over the Southeast US. The lifetime of the primary INs to Reactions (R3) + (R4b) is constrained by the MCM rate constants, limiting the range of potential effective lifetimes for isoprene nitrates to less than 5 h in the model. The results from four different model scenarios using different combinations of α_isop and IN lifetime (tuned by varying the rate of Reaction (R2) for the secondary INs) are shown in Table 2 (ANs.3–ANs.6).

Introducing this NO₂ recycling mechanism to the model has a dramatic effect on the ΣANs/NOₓ ratio, resulting in a 104% underestimation in the first case (ANs.3: α=8%, τ=2.5 h) and a 123% underestimation in the second case (ANs.4: α=12%, τ=100 min). The model can be improved by progressively lowering α, while simultaneously increasing in the secondary ANs lifetime. However, even at the deposition-limited lifetime for the secondary isoprene nitrates (8 h) the ΣANs/NOₓ ratio is underestimated by 50% (ANs.5: using the corresponding α=6%, with an effective τ=4.9 h). The highest possible IN yield and lifetime (ANs.6: α=12%, τ=4.5 h) still underestimates the ΣANs/NOₓ ratio by 36%. In all of these cases, the NO₂ recycling mechanism leads to an underestimation of the amount of ΣANs produced at a given NOₓ abundance. The ΣANs/NOₓ ratio was found to be sensitive to the soil NOₓ source strength, increasing with decreasing emissions; setting the NOₓ emissions to zero improves the model predictions by about 10–15%.

If the N-containing product of Reaction (R2b) were HNO₃ instead of NO₂, the ΣANs/NOₓ ratio would improve; this would, however, be inconsistent with the HNO₃/NOₓ ratio, as it is already overestimated (see Sect. 4.5). Assuming this chemistry is correct, we find that we can close the gap between the model and the observations, while including the Paulot isoprene nitrate mechanism, if nearly 100% of the non-isoprene alkyl nitrates retain their nitrate functionality upon oxidation by OH. As these nitrates are mostly MBO-derived, one interpretation of these results is that a significant fraction of MBO-derived nitrates reacts primarily via (R2a). Additionally, while terpene-derived nitrates are calculated to be a minor fraction of ΣANs, there is substan-
tial uncertainty in their secondary chemistry and they may in fact be a larger fraction of ΣANs in the region. Other possibilities of paired errors, of course, exist. A better understanding of the production and fate of nitrates from MBO and terpene oxidation is required to adequately constrain ΣANs chemistry in the region.

4.5 HNO₃

Nitric acid accounts for 25% of the initial ΣNOₓ concentration and 32% of the ΣNOₓ observed at UC-BFRS. Its mixing ratios along the transect are controlled by production due to reaction of OH with NO₂, entrainment of air with a lower concentration (62%), and loss to deposition (37%). Loss of HNO₃ to oxidation by OH accounts for less than 1% of the loss of HNO₃. The Reference model HNO₃ is within a few percent of the observations, however, the HNO₃/NOₓ ratio is overestimated by 14%.

HNO₃ concentration at UC-BFRS is sensitive to the assumptions made with respect to the ΣPNs and ΣANs chemistry, as discussed above. In a revised model (Rev. in Table 2), which incorporates changes to the ΣPNs chemistry and allows for NO₂ recycling by isoprene nitrates as discussed above, the concentration of HNO₃ increases relative to the reference model due higher sustained NOₓ as a result of increased recycling from ΣANs and a lower concentration of ΣPNs precursors. The HNO₃/NOₓ ratio is overestimated by 12% in the revised model, slightly lower than that in the Reference model.

Tuning of the average ΣANs branching ratio, the yield of Reaction (R2), and the acyl peroxy radical production rate in the model can simultaneously minimize the error in the HNO₃/NOₓ, ΣANs/NOₓ, and ΣPNs/NOₓ ratios to under 10% for each. It is suspected, therefore, that uncertainties in the chemistry of ΣPNs and ΣANs are linked to the discrepancy between the modeled and observed HNO₃/NOₓ ratio.
5 Atmosphere-biosphere exchange of nitrogen

5.1 Soil NO\textsubscript{x} emissions

Herman et al. (2003) made measurements of soil NO\textsubscript{x} emissions in the oak forests of the Sierra Nevada foothills to the west of UC-BFRS. They observed fluxes in the range of 5.8 to 15 ppt m s\textsuperscript{-1} (3.3 to 8.6 ng (N) m\textsuperscript{-2} s\textsuperscript{-1}) in the summer which is a total source of 0.131 to 0.338 ppb if the emissions are assumed to be constant between Granite Bay and UC-BFRS. A soil NO\textsubscript{x} source in the middle of this range (10 ppt m s\textsuperscript{-1}) was chosen.

In order to understand the effects of soil NO\textsubscript{x} emissions, we ran a zero soil emissions scenario for the Reference model (\(E_{NO\textsubscript{x}}\) 0, in Table 2). In this case, the absence of a soil NO\textsubscript{x} source leads to a worsening of the agreement of the NO\textsubscript{x}/NO\textsubscript{y} ratio from a 2% underestimate to a 10% underestimate. Total NO\textsubscript{y} at UC-BFRS decreases in the model by about 100 ppt or 4% in the absence of soil NO\textsubscript{x} emissions. An important result is that modeled ozone concentrations are little affected by this change. A soil NO\textsubscript{x} source of 45 ppt m s\textsuperscript{-1} (25.8 ng (N) m\textsuperscript{-2} s\textsuperscript{-1}), 3 times larger than prior observations, is required to match observations of total NO\textsubscript{y}; however, an accompanying increase in HO\textsubscript{x} radical concentrations would be required to keep the NO\textsubscript{x}/NO\textsubscript{z} ratio in agreement.

We conclude that a soil NO\textsubscript{x} source in the range of observations by Herman et al. (2003) is consistent with the observed NO\textsubscript{x}/NO\textsubscript{y} ratio, but has little effect on the total NO\textsubscript{y} abundance or on ozone production. It should be noted that these conclusions are sensitive to the imposed NO\textsubscript{x} background in the model of 100 ppt and they suggest that the background is sustained by soil NO\textsubscript{x} emissions.

5.2 Nitrogen deposition

The model allows us to estimate the extent of N deposition, facilitated by the conversion of NO\textsubscript{x} to NO\textsubscript{z}, that occurs in the downwind regions of the Sacramento urban area. While speciation within the NO\textsubscript{z} class is important due to differences in deposition
rates for $\Sigma$PNs vs. $\Sigma$ANs vs. HNO$_3$, and while there are known errors in the model with respect to $\Sigma$ANs and $\Sigma$PNs chemistry, nevertheless, first-order approximations can be made about the magnitude of N deposition along the model transect because of the agreement between observed and modeled NO$_x$/NO$_z$ ratios, particularly in the Reference model.

We use the $V_{\text{dep}}$ calculated by Farmer and Cohen (Farmer and Cohen, 2008) to represent deposition of $\Sigma$PNs, $\Sigma$ANs and HNO$_3$. The deposition falls off as the plume is advected from Granite Bay. In the Reference model, the N-deposition ranges from 82 ng (N) m$^{-2}$ s$^{-1}$ at Granite Bay to 26 ng (N) m$^{-2}$ s$^{-1}$ at UC-BFRS. Of the total N deposited, 79% is due to HNO$_3$ deposition, 11% to $\Sigma$ANs deposition and 10% to the deposition of $\Sigma$PNs. The average deposition throughout the transect is 55 ng (N) m$^{-2}$ s$^{-1}$ which is approximately 17 kg (N) ha$^{-1}$ yr$^{-1}$. Bytnerowicz and Fenn (1996) report values that range from 0.5 to 35 kg (N) ha$^{-1}$ yr$^{-1}$ for California based on measurements of NO$_3^-$ and NH$_4^+$ rinsed off of foliage. Tarnay et al. (2001) estimate the flux of nitrogen to the Lake Tahoe Basin to be 1.7 to 2.9 kg N ha$^{-1}$ yr$^{-1}$ based on measurements of HNO$_3$ and NH$_3$. These values are lower than those obtained in this study because of the lower concentration of nitrogen species further away from the source region (Sacramento).

The nitrogen deposition rate calculated here is much larger than the rate of N emission from soils estimated in the model (2 ng (N) m$^{-2}$ s$^{-1}$ or 0.6 kg (N) ha$^{-1}$ yr$^{-1}$), suggesting a net accumulation of nitrogen in the region’s ecosystem of 16 kg (N) ha$^{-1}$ yr$^{-1}$.

6 Conclusions

A Lagrangian box model representing mixing, photochemistry and dry deposition was used to describe the evolution of the plume originating in the Sacramento Area as it is advected into the western Sierra. The model was used to consider effects of a variety of poorly understood processes that affect the chemical evolution of organic nitrogen within the plume. Comparisons of the model with observations of NO$_y,i$ at UC-BFRS show that the model captures many of the observed features of the plume chemistry.
of NO\textsubscript{y}. This is the first such model that provides a detailed representation of the partitioning of NO\textsubscript{y} in an urban plume backed by observations of NO\textsubscript{x}, ΣANs, ΣPNs, and HNO\textsubscript{3}.

We find that significant deviations from observations of speciated PNs at UC-BFRS (LaFranchi et al., 2009; Wolfe et al., 2009) and elsewhere (Roberts et al., 2007; Wooldridge et al., 2009) occur in the model when lumped aldehydes are given the opportunity to form PNs indiscriminately and with the same efficiency as PAN. A PAN/ΣPNs ratio of 80%, in good agreement with observations, can be attained if this lumped PN species is not allowed to form and is accompanied by an increase in the concentration of PAN precursors.

We also find that there is significant uncertainty surrounding the production and fate of ΣANs. Incorporating recent findings about isoprene nitrate chemistry into the model leads to large errors in ΣANs abundance. Given these new constraints on isoprene nitrates, the results indicate that the reaction of other ANs with OH must produce more oxidized ΣANs, as opposed to HNO\textsubscript{3} or NO\textsubscript{2} as is present in other models. It is recommended that future laboratory and modeling experiments focus on understanding the formation yield and NO\textsubscript{x} recycling rate for MBO- and terpene-derived nitrates.

Finally, model results show that adding biogenic NO\textsubscript{x} emissions throughout the transect increases the available NO\textsubscript{x} at UC-BFRS, but modeled ozone concentrations were little affected by the increased biogenic NO\textsubscript{x}. Nitrogen deposition is estimated to be 17 kg (N) ha\textsuperscript{-1} yr\textsuperscript{-1}, on average, along the model transect leading to a net nitrogen accumulation in the biosphere of 16 kg (N) ha\textsuperscript{-1} yr\textsuperscript{-1} through exchange with the atmosphere.
Appendix A

Chemical mechanism

Definitions used in the following mechanism:

$RO_2 \equiv$ non-speciated organic peroxy radical

$RCOO_2 \equiv$ non-speciated peroxy acyl radical

$\Sigma RO_2 \equiv \Sigma RO_2 + \Sigma RCOO_2$ (both speciated and non-speciated)

Aldehyde $\equiv$ non-speciated aldehyde

$RONO_2 \equiv$ non-speciated alkyl nitrate

$IN-OH \equiv$ second generation isoprene nitrate (hydroxy alkyl nitrate)

$\gamma \equiv NO_2$ yield for $IN-OH$+$OH$ reactions (0% or 50%)

$RCOO_2NO_2 \equiv$ non-speciated peroxy acyl nitrate

$ROOH \equiv$ non-speciated organic peroxide

Benzene + OH $\rightarrow$ 0.648 HO$_2$ + 0.352 AromaticO$_2$ + 0.118 Aldehyde \hfill (A1)

Ethylbenzene + OH $\rightarrow$ 0.28 HO$_2$ + 0.72 AromaticO$_2$ + 0.1 Aldehyde \hfill (A2)

Toluene + OH $\rightarrow$ 0.28 HO$_2$ + 0.72 AromaticO$_2$ + 0.1 Aldehyde \hfill (A3)
\[ \begin{align*}
    m\text{-xylene} + \text{OH} & \rightarrow 0.46 \text{HO}_2 + 0.54 \text{AromaticO}_2 + 0.29 \text{Aldehyde} \quad (A4) \\
    o\text{-xylene} + \text{OH} & \rightarrow 0.40 \text{HO}_2 + 0.6 \text{AromaticO}_2 + 0.24 \text{Aldehyde} \quad (A5) \\
    p\text{-xylene} + \text{OH} & \rightarrow 0.275 \text{HO}_2 + 0.725 \text{AromaticO}_2 + 0.115 \text{Aldehyde} \quad (A6) \\
    \text{CH}_2\text{O} + \text{OH} & \rightarrow \text{HO}_2 + \text{CO} \quad (A7) \\
    \alpha\text{-pinene} + \text{OH} & \rightarrow 0.44 \text{HO}_2 + 0.1 \text{acetone} + 0.44 \text{pinonaldehyde} \quad (A8) \\
    \text{HCOCO}_2\text{H} + \text{OH} & \rightarrow \text{HO}_2 + \text{CO} \quad (A9) \\
    \text{Isopaoh} + \text{OH} & \rightarrow \text{HO}_2 + 0.5 \text{HC}_4\text{CCHO} + 0.5 \text{HC}_4\text{ACHO} \quad (A10) \\
    \text{Isopboh} + \text{OH} & \rightarrow 0.75 \text{HO}_2 + \text{IsopbO}_2 + 0.25 \text{CH}_3\text{O}_2 + 0.75 \text{CH}_2\text{O} + 0.75 \text{MVK} + 0.25 \text{MVKOH} \quad (A11) \\
    \text{Isopdoh} + \text{OH} & \rightarrow \text{HO}_2 + \text{HCOC5} \quad (A12) \\
    \text{Glyoxal} + \text{OH} & \rightarrow 0.6 \text{HO}_2 + 0.4 \text{HCOCO}_3 + 1.2 \text{CO} \quad (A13) \\
    \text{Acetol} + \text{OH} & \rightarrow \text{HO}_2 + \text{Mgly} \quad (A14) \\
    \text{HOCH}_2\text{CO}_2\text{H} + \text{OH} & \rightarrow \text{HO}_2 + \text{CH}_2\text{O} \quad (A15) \\
    \text{MACROH} + \text{OH} & \rightarrow \text{HO}_2 + \text{CH}_2\text{O} + \text{ACETOL} \quad (A16) \\
    \text{MACROOH} + \text{OH} & \rightarrow \text{MACRO}_2 \quad (A17) \\
    \text{HOCH}_2\text{CHO} + \text{OH} & \rightarrow 0.2 \text{HO}_2 + 0.8 \text{RCOO}_2 + 0.2 \text{glyoxal} \quad (A18) \\
    \text{ACO}_2\text{H} + \text{OH} & \rightarrow \text{HO}_2 + \text{CO} + \text{CH}_2\text{O} \quad (A19) \\
    \text{HO12CO}_3\text{C4} + \text{OH} & \rightarrow \text{HO}_2 + \text{BIACETOH} \quad (A20) 
\end{align*} \]
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\[ \text{HC}_4\text{ACO}_2\text{H} + \text{OH} \rightarrow \text{HO}_2 + \text{CO} + \text{ACETOL} \quad \text{(A21)} \]

\[ \text{MBOACO} + \text{OH} \rightarrow \text{HO}_2 + \text{MBOCOCO} \quad \text{(A22)} \]

\[ \text{MBOBCO} + \text{OH} \rightarrow \text{C}_4\text{OH}_2\text{CO}_3 \quad \text{(A23)} \]

\[ \text{MBOAOH} + \text{OH} \rightarrow \text{HO}_2 + \text{MBOACO} \quad \text{(A24)} \]

\[ \text{ipropol} + \text{OH} \rightarrow 0.861 \text{HO}_2 \quad \text{(A25)} \]

\[ \text{IPRHO} \text{CO}_2\text{H} + \text{OH} \rightarrow \text{HO}_2 + \text{acetone} \quad \text{(A26)} \]

\[ \text{Methanol} + \text{OH} \rightarrow \text{HO}_2 + \text{CH}_2\text{O} \quad \text{(A27)} \]

\[ \text{n-butane} + \text{OH} \rightarrow \text{RO}_2 \quad \text{(A28)} \]

\[ \text{hexane} + \text{OH} \rightarrow \text{RO}_2 \quad \text{(A29)} \]

\[ \text{i-butane} + \text{OH} \rightarrow \text{RO}_2 \quad \text{(A30)} \]

\[ \text{i-pentane} + \text{OH} \rightarrow \text{RO}_2 \quad \text{(A31)} \]

\[ \text{n-pentane} + \text{OH} \rightarrow \text{RO}_2 \quad \text{(A32)} \]

\[ \text{methylpentanes} + \text{OH} \rightarrow \text{RO}_2 \quad \text{(A33)} \]

\[ \text{heptane} + \text{OH} \rightarrow \text{RO}_2 \quad \text{(A34)} \]

\[ 2,2\text{-dimethylpropane} + \text{OH} \rightarrow \text{RO}_2 \quad \text{(A35)} \]

\[ \text{C}_2\text{Cl}_4 + \text{OH} \rightarrow \text{RO}_2 \quad \text{(A36)} \]

\[ \text{CH}_2\text{Cl}_2 + \text{OH} \rightarrow \text{RO}_2 \quad \text{(A37)} \]

\[ \text{CH}_3\text{Cl} + \text{OH} \rightarrow \text{RO}_2 \quad \text{(A38)} \]
Cyclopentane + OH → RO₂
MTBE + OH → RO₂
1-butene + OH → RO₂
Propyne + OH → RO₂
Ethane + OH → RO₂
Ethanol + OH → RO₂ + 0.95 HO₂ + 0.887 acetaldehyde
1,3-butadiene + OH → RO₂
C2-pentene + OH → RO₂
cyclopentene + OH → RO₂
MEK + OH → RO₂ + 0.2772 acetaldehyde
2-methylpropene + OH → RO₂
1-pentene + OH → RO₂
Propane + OH → RO₂
Propene + OH → RO₂
t₂-butene + OH → RO₂
t₂-pentene + OH → RO₂
3-methyl-1-butene + OH → RO₂
2-methyl-1-butene + OH → RO₂
\[ \alpha - \text{pinene} + \text{OH} \rightarrow 0.82 \text{RO}_2 + 0.21 \text{CH}_2\text{O} \] (A57)

\[ \text{pinonaldehyde} + \text{OH} \rightarrow 0.228 \text{RO}_2 + 0.772 \text{RCOO}_2 \] (A58)

\[ \text{acetone} + \text{OH} \rightarrow \text{RO}_2 \] (A59)

\[ \text{HCOC5} + \text{OH} \rightarrow \text{RO}_2 \] (A60)

\[ \text{MVKOH} + \text{OH} \rightarrow \text{RO}_2 \] (A61)

\[ \text{isopropyl} + \text{OH} \rightarrow 0.139 \text{RO}_2 + 0.861 \text{acetone} \] (A62)

\[ \text{pentanal} + \text{OH} \rightarrow 0.19 \text{RO}_2 + 0.81 \text{RCOO}_2 \] (A63)

\[ \text{isoprene} + \text{OH} \rightarrow 0.164 \text{IsopaO}_2 + 0.491 \text{IsopbO}_2 + 0.086 \text{IsopcO}_2 + 0.259 \text{IsopdO}_2 \] (A64)

\[ \text{MVK} + \text{OH} \rightarrow 0.3 \text{HMVKAO}_2 + 0.7 \text{HMVKBO}_2 \] (A65)

\[ \text{MACR} + \text{OH} \rightarrow 0.43 \text{MACRO}_2 + 0.57 \text{MACRO3} \] (A66)

\[ \text{HC}_4\text{CCHO} + \text{OH} \rightarrow 0.52 \text{C57O}_2 + 0.48 \text{HC}_4\text{CCO}_3 \] (A67)

\[ \text{HC}_4\text{ACHO} + \text{OH} \rightarrow 0.52 \text{C58O}_2 + 0.48 \text{HC}_4\text{ACO}_3 \] (A68)

\[ \text{CH}_4 + \text{OH} \rightarrow \text{CH}_3\text{O}_2 \] (A69)

\[ \text{CH}_3\text{CO}_2\text{H} + \text{OH} \rightarrow \text{CH}_3\text{O}_2 \] (A70)

\[ \text{CH}_3\text{COOH} + \text{OH} \rightarrow \text{CH}_3\text{O}_2 \] (A71)

\[ \text{MBO} + \text{OH} \rightarrow 0.67 \text{MBOAO}_2 + 0.33 \text{MBOBO}_2 \] (A72)

\[ \text{MBOAOOH} + \text{OH} \rightarrow \text{MBOAO}_2 + \text{MBOACO} \] (A73)
MBOBOOH + OH → MBOBO₂ + MBOBCO  

Hexanal + OH → RCOO₂  

HC₄CCO₂H + OH → RCOO₂  

HOCH₂COCHO + OH → RCOO₂  

HC₄ACO₂H + OH → RCOO₂  

Aldehyde + OH → RCOO₂  

HC₃COO₂H + OH → HC₃COO₃  

MACO₂H + OH → MACO₃  

mgly + OH → CH₃CO₂ + CO  

HC₄CCO₂H + OH → CH₃CO₂ + HOCH₂CHO  

CO₂₃C₃CHO + OH → CH₃CO₂ + 2 CO  

CH₃COCO₂H + OH → CH₃CO₂  

MACO₂H + OH → CH₃CO₂ + CH₂O  

Acetaldehyde + OH → CH₃CO₂  

ACO₂H + OH → ACO₃  

Vglyox + OH → ACO₃ + CO  

CO₂₃HCHO + OH → CO₂₃HCO₃  

C₄OH₂CO₃H + OH → C₄OH₂CO₃
Ibutaloh + OH → IPRHOCO₃  
IPRHOCO₃H + OH → IPRHOCO₃  
MBOBCOCO + OH → IPRHOCO₃ + CO  
IsopaNO₃ + OH → IsopaNO₃O₂  
IsopbNO₃ + OH → IsopbNO₃O₂  
IsopcNO₃ + OH → IsopcNO₃O₂  
IsopdNO₃ + OH → IsopcNO₃O₂  
C58NO₃ + OH → NO₂ + Aldehyde  
HMVKANO₃ + OH → NO₂ + Aldehyde  
AromaticNO₃ + OH → NO₂ + Aldehyde  
MBOANO₃ + OH → NO₂ + Aldehyde  
MBOBNO₃ + OH → NO₂ + Aldehyde  
IN-OH + OH → NO₂ + Aldehyde  
RONO₂ + OH → NO₂ + Aldehyde  
CH₃NO₃ + OH → NO₂ + CH₂O  
PAN + OH → NO₂ + CO + CH₂O  
C4PAN5 + OH → NO₂ + CO + acetone  
C4OH2CPAN + OH → NO₂ + CO + Ibutaloh
RCOO₂NO₂ + OH → NO₂ + Aldehyde  
ACRPAN + OH → NO₂ + CO + HOCH₂CHO  
MPAN + OH → NO₂ + CO + ACETOL  
GLYPAN + OH → NO₂ + CO  
C₅PAN₁₉ + OH → NO₂ + CO + HO₁₂CO₃C₄  
C₄PAN₆ + OH → NO₂ + CO + Mgly  
C₅PAN₁₇ + OH → NO₂ + CO + MACROH  
CO + OH → HO₂  
ISOPAOOH + OH → HC₄ACHO  
ISOPBOOH + OH → Isopbo2  
ISOPCOOH + OH → HC₄CCHO  
ISOPDOOH + OH → HCOC₅  
C₅₈OH + OH → glyoxal + ACETOL  
C₅₇OOH + OH → C₅₇O₂  
BIACETOH + OH → CO₂₃C₃CHO  
CO₂H₃CO₃H + OH → CO₂H₃CO₃  
HMVKBOOH + OH → BIACETOH  
CH₃OÖH + OH → CH₃O₂
HMVKAOOH + OH → CO$_2$H$_3$CHO  
C58OOH + OH → C58O$_2$  
MVKOOH + OH → VGLYOX  
MBOCOCO + OH → CO + IPRHOCO$_3$  
HCOOH + OH → HO$_2$  
CH$_3$CO$_3$H + OH → CH$_3$CO$_3$  
Isopao$_2$ + Σ RO$_2$ → 0.8 HO$_2$ + 0.1 Isopaoh + 0.8 HC$_4$CCHO + 0.1 HC$_4$ACHO  
Isopbo$_2$ + Σ RO$_2$ → 0.6 HO$_2$ + 0.1856 CH$_3$O$_2$ + 0.6 CH$_2$O + 0.6 MVK + 0.2 MVKOH + 0.2 Isopboh  
Isopco$_2$ + Σ RO$_2$ → 0.8 HO$_2$ + 0.8 CH$_2$O + 0.1 Isopaoh + 0.1 HC$_4$CCHO + 0.8 HC$_4$ACHO  
Isopdo$_2$ + Σ RO$_2$ → 0.8 HO$_2$ + 0.8 MACR + 0.1 HCOC$_5$ + 0.1 IsopdOH  
Isopao$_2$ + NO → 0.892 HO$_2$ + 0.892 NO$_2$ + 0.108 IsopaNO$_3$ + 0.892 HC$_4$CCHO  
Isopbo$_2$ + NO → 0.947 HO$_2$ + 0.237 CH$_3$O$_2$ + 0.947 NO$_2$ + 0.710 CH$_2$O + 0.710 MVK + 0.053 IsopbNO$_3$ + 0.237 MVKOH  
Isopco$_2$ + NO → 0.902 HO$_2$ + 0.902 NO$_2$ + 0.08 IsopcNO$_3$ + 0.902 HC$_4$ACHO  
Isopdo$_2$ + NO → 0.893 HO$_2$ + 0.893 NO$_2$ + 0.893 CH$_2$O + 0.893 MACR + 0.107 IsopdNO$_3$
Isopao2 + HO₂ → 0.706 ISOPAOOH  
(A142)

Isopbo2 + HO₂ → 0.706 ISOPBOOH  
(A143)

Isopco2 + HO₂ → 0.706 ISOPCOOH  
(A144)

Isopdo2 + HO₂ → 0.706 ISOPDOOH  
(A145)

IsopaNO₃O₂ + HO₂ → IN-OH  
(A146)

IsopbNO₃O₂ + HO₂ → IN-OH  
(A147)

IsopcNO₃O₂ + HO₂ → IN-OH  
(A148)

IsopdNO₃O₂ + HO₂ → IN-OH  
(A149)

IsopaNO₃O₂ + Σ RO₂ → IN-OH  
(A150)

IsopbNO₃O₂ + Σ RO₂ → IN-OH  
(A151)

IsopcNO₃O₂ + Σ RO₂ → IN-OH  
(A152)

IsopdNO₃O₂ + Σ RO₂ → IN-OH  
(A153)

IsopaNO₃O₂ + NO → γ NO₂ + γ Aldehyde + (1 − γ) IN-OH  
(A154)

IsopbNO₃O₂ + NO → γ NO₂ + γ Aldehyde + (1 − γ) IN-OH  
(A155)

IsopcNO₃O₂ + NO → γ NO₂ + γ Aldehyde + (1 − γ) IN-OH  
(A156)

IsopdNO₃O₂ + NO → γ NO₂ + γ Aldehyde + (1 − γ) IN-OH  
(A157)

MVKO₂ + Σ RO₂ → 0.6 ACO₃ + 0.6 CH₂O + 0.2 MVKOH + 0.2 VGLYOX + 0.2 MVKOOnH  
(A158)
\[ \text{FMVKO}_2 + \text{NO} \rightarrow \text{ACO}_3 + \text{NO}_2 + \text{CH}_2\text{O} \]  
\[ \text{FMVKO}_2 + \text{HO}_2 \rightarrow 0.625 \text{FMVKOOH} \]  
\[ \text{HMVKAO}_2 + \Sigma \text{RO}_2 \rightarrow 0.6 \text{HO}_2 + 0.6 \text{CH}_2\text{O} + 0.6 \text{Mgly} + 0.2 \text{CO}_2\text{H}_3\text{CHO} + 0.2 \text{HO12CO}_3\text{C4} \]  
\[ \text{HMVKAO}_2 + \text{NO} \rightarrow 0.983 \text{HO}_2 + 0.983 \text{NO}_2 + 0.983 \text{CH}_2\text{O} + 0.98 \text{Mgly} + 0.017 \text{HMVKANO}_3 \]  
\[ \text{HMVKAO}_2 + \text{HO}_2 \rightarrow 0.625 \text{HMVKAOOH} \]  
\[ \text{HMVKBO}_2 + \Sigma \text{RO}_2 \rightarrow 0.6 \text{CH}_3\text{CO}_3 + 0.6 \text{HOCH}_2\text{CHO} + \text{BIACETOH} + 0.2 \text{HO12CO}_3\text{C4} \]  
\[ \text{HMVKBO}_2 + \text{NO} \rightarrow \text{CH}_3\text{CO}_3 + \text{NO}_2 + \text{HOCH}_2\text{CHO} \]  
\[ \text{HMVKBO}_2 + \text{HO}_2 \rightarrow 0.625 \text{HMVKBOOH} \]  
\[ \text{MACRO}_2 + \Sigma \text{RO}_2 \rightarrow 0.7 \text{HO}_2 + 0.3 \text{MACROH} + 0.7 \text{ACETOL} \]  
\[ \text{MACRO}_2 + \text{NO} \rightarrow \text{HO}_2 + \text{NO}_2 + \text{ACETOL} \]  
\[ \text{MACRO}_2 + \text{HO}_2 \rightarrow 0.625 \text{MACROOH} \]  
\[ \text{C57O}_2 + \Sigma \text{RO}_2 \rightarrow 0.7 \text{HO}_2 + 0.7 \text{Mgly} + 0.7 \text{HOCH}_2\text{CHO} \]  
\[ \text{C57O}_2 + \text{NO} \rightarrow \text{HO}_2 + \text{NO}_2 + \text{Mgly} + \text{HOCH}_2\text{CHO} \]  
\[ \text{C57O}_2 + \text{HO}_2 \rightarrow 0.706 \text{C57OOH} \]  
\[ \text{C58O}_2 + \Sigma \text{RO}_2 \rightarrow 0.7 \text{HO}_2 + 0.7 \text{glyoxal} + \text{ACETOL} + 0.3 \text{C58OH} \]
C58O₂ + NO → 0.981 HO₂ + 0.981 NO₂ + 0.019 C58NO₃ + 0.981 glyoxal + 0.981 ACETOL (A174)

C58O₂ + HO₂ → 0.706 C58OOH (A175)

CH₃O₂ + Σ RO₂ → HO₂ + 0.665 CH₂O + 0.335 Methanol (A176)

CH₃O₂ + NO → 0.999 HO₂ + 0.999 NO₂ + 0.999 CH₂O + 0.001 CH₃NO₃ (A177)

CH₃O₂ + HO₂ → CH₃OOH (A178)

MBOAO₂ + Σ RO₂ → 0.6 HO₂ + 0.6 acetone + 0.6 HOCH₂CHO + 0.2 MBOAOH + 0.2 MBOACO (A179)

MBOAO₂ + NO → 0.936 HO₂ + 0.936 acetone + 0.936 HOCH₂CHO + 0.064 MBOANO₃ (A180)

MBOAO₂ + HO₂ → 0.706 MBOAOOH (A181)

MBOBO₂ + Σ RO₂ → 0.6 HO₂ + 0.6 CH₂O + 0.6 Ibutaloh + 0.2 MBOAOH + 0.2 MBOBCO (A182)

MBOBO₂ + NO → 0.974 HO₂ + 0.974 CH₂O + 0.974 Ibutaloh + 0.026 MBOBNO₃ (A183)

MBOBO₂ + HO₂ → 0.706 MBOBOOH (A184)

AromaticO₂ + Σ RO₂ → HO₂ (A185)

AromaticO₂ + NO → 0.9 HO₂ + 0.9 NO₂ + 0.1 Aldehyde (A186)

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AromaticO₂ + HO₂ → 0.9 Aldehyde + AromaticOOH  \hspace{1cm} (A187)
HCOCO₃ + Σ RO₂ → 0.7 HO₂ + 0.7 CO + 0.3 HCOCO₂H \hspace{1cm} (A188)
HCOCO₃ + NO → HO₂ + NO₂ + CO \hspace{1cm} (A189)
HCOCO₃ + HO₂ → 0.29 HCOCO₂H + 0.71 HCOCO₃H \hspace{1cm} (A190)
HCOCO₃ + NO₂ + M → GLYPAN + M  \hspace{1cm} (A191)
MACO₃ + Σ RO₂ → 0.7 CH₃CO₃ + 0.7 CH₂O + 0.3 MACO₂H \hspace{1cm} (A192)
MACO₃ + NO → CH₃CO₃ + NO₂ + 0.7 CH₂O \hspace{1cm} (A193)
MACO₃ + HO₂ → 0.71 MACO₃H + 0.29 MACO₂H \hspace{1cm} (A194)
MACO₃ + NO₂ + M → MPAN + M \hspace{1cm} (A195)
CH₃CO₃ + Σ RO₂ → 0.7 CH₃O₂ + 0.3 CH₃CO₂H  \hspace{1cm} (A196)
CH₃CO₃ + NO → CH₃O₂ + NO₂ \hspace{1cm} (A197)
CH₃CO₃ + HO₂ → 0.29 CH₃CO₂H + 0.71 CH₃CO₃H \hspace{1cm} (A198)
CH₃CO₃ + NO₂ + M → PAN + M \hspace{1cm} (A199)
ACO₃ + Σ RO₂ → 0.7 HO₂ + CO + 0.7 CH₂O + 0.3 ACO₂H \hspace{1cm} (A200)
ACO₃ + NO → HO₂ + NO₂ + CO + CH₂O \hspace{1cm} (A201)
ACO₃ + HO₂ → 0.29 ACO₂H + 0.71 ACO₃H \hspace{1cm} (A202)
ACO₃ + NO₂ → ACRPAN + M \hspace{1cm} (A203)
HC₄CCHO₃ + Σ RO₂ → 0.7 CH₃CO₃ + 0.3 HC₄CCHO₂H + 0.7 HOCH₂CHO \hspace{1cm} (A204)
HC$_4$CCO$_3$ + NO $\rightarrow$ CH$_3$CO$_3$ + NO$_2$ + HOCH$_2$CHO (A205)

HC$_4$CCO$_3$ + HO$_2$ $\rightarrow$ 0.29 HC$_4$CCO$_2$H + 0.71 HC$_4$CCO$_3$H (A206)

HC$_4$CCO$_3$ + NO$_2$ + M $\rightarrow$ C5PAN19 + M (A207)

HC$_4$ACO$_3$ + $\Sigma$ RO$_2$ $\rightarrow$ 0.7 HO$_2$ + 0.7 CO + 0.7 ACETOL + 0.3 HC$_4$ACO$_2$H (A208)

HC$_4$ACO$_3$ + NO $\rightarrow$ HO$_2$ + NO$_2$ + CO + ACETOL (A209)

HC$_4$ACO$_3$ + HO$_2$ $\rightarrow$ 0.29 HC$_4$ACO$_2$H + 0.71 HC$_4$ACO$_3$H (A210)

HC$_4$ACO$_3$ + NO$_2$ + M $\rightarrow$ C5PAN17 + M (A211)

CO$_2$H$_3$CO$_3$ + $\Sigma$ RO$_2$ $\rightarrow$ HO$_2$ + Mgly (A212)

CO$_2$H$_3$CO$_3$ + NO $\rightarrow$ HO$_2$ + NO$_2$ (A213)

CO$_2$H$_3$CO$_3$ + HO$_2$ $\rightarrow$ CO$_2$H$_3$CO$_3$H (A214)

CO$_2$H$_3$CO$_3$ + NO$_2$ + M $\rightarrow$ C4PAN6 + M (A215)

C$_4$OH$_2$CO$_3$ + $\Sigma$ RO$_2$ $\rightarrow$ HO$_2$ + Ibutiloh (A216)

C$_4$OH$_2$CO$_3$ + NO $\rightarrow$ HO$_2$ + NO$_2$ + Ibutiloh (A217)

C$_4$OH$_2$CO$_3$ + HO$_2$ $\rightarrow$ C$_4$OH$_2$CO$_3$H (A218)

C$_4$OH$_2$CO$_3$ + NO$_2$ + M $\rightarrow$ C4OH2CPAN + NO$_2$ + M (A219)

IPRHOOCO$_3$ + $\Sigma$ RO$_2$ $\rightarrow$ 0.7 HO$_2$ + 0.7 acetone + 0.3 IPRHOOCO$_2$H (A220)

IPRHOOCO$_3$ + NO $\rightarrow$ HO$_2$ + NO$_2$ + acetone (A221)

IPRHOOCO$_3$ + HO$_2$ $\rightarrow$ 0.29 IPRHOOCO$_2$H + 0.71 IPRHOOCO$_3$H (A222)
IPRHOOCO₃ + NO₂ + M → C4PAN5 + NO₂ + M \hspace{1cm} (A223)

Isoprene + O₃ → 0.2625 HO₂ + 0.27 OH + 0.044 MVKOO + 0.054 MVKO₂\hspace{1cm} (A224)
+ 0.066 MACROO + 0.051 CH₃O₂ + 0.11 CH₂OO + 0.1575 CH₃CO₃
+ 0.522 CO + 0.7085 CH₂O + 0.3 MACR + 0.2 MVK + 0.1275 propene

MVK + O₃ → 0.28 HO₂ + 0.36 OH + 0.12 MGLOO + 0.12 CH₂OO \hspace{1cm} (A225)
+ 0.28 CH₃CO₃ + 0.56 CO + 0.75 CH₂O + 0.1 acetaldehyde + 0.5 Mgly

MACR + O₃ → 0.41 HO₂ + 0.82 OH + 0.09 MGLYOO + 0.09 CH₂OO \hspace{1cm} (A226)
+ 0.41 CH₃CO₃ + 0.82 CO + 0.5 CH₂O + 0.5 Mgly

HC₄CCHO + O₃ → 0.445 HO₂ + 0.89 OH + 0.055 GAOO + 0.055 MGLYOO \hspace{1cm} (A227)
+ 0.445 CH₃CO₃ + 0.89 CO + 0.445 CH₂O + 0.5 Mgly
+ 0.5 HOCH₂CHO

HC₄ACHO + O₃ → 0.89 HO₂ + 0.89 OH + 0.055 GLYOO + 0.055 ACLOO \hspace{1cm} (A228)
+ 0.89 CO + 0.5 glyoxal + 0.5 ACETOL

MVKOH + O₃ → 0.18 HO₂ + 0.46 OH + 0.12 HMGLOO + 0.12 CH₂OO \hspace{1cm} (A229)
+ 0.28 RCOO₂ + 0.57 CO + 0.5 CH₂O + 0.1 HOCH₂CHO
+ 0.5 HOCH₂COCHO

MBO + O₃ → 0.48 HO₂ + 0.36 OH + 0.072 MBOOO + 0.168 CH₂OO \hspace{1cm} (A230)
+ 0.64 CO + 0.3 CH₂O + 0.168 acetone + 0.7 Ibutilphol + 0.06 ipropol

α-pinene + O₃ → 0.81 OH + 0.185 CH₂O + 0.6 acetone + 0.26 pinonaldehyde \hspace{1cm} (A231)
Propene + O₃ → 0.28 HO₂ + 0.36 OH + 0.28 CH₃O₂
  +0.12 CH₂OO + 0.12 CH₃CHO + 0.56 CO + 0.5 CH₂O
  +0.5 acetaldehyde

1-butene + O₃ → 0.28 HO₂ + 0.78 RO₂ + 0.36 OH + 0.12 CH₂OO + 0.56 CO
  +0.5 CH₂O + 0.1 ethane + 0.12 Aldehyde

1-butene + O₃ → 0.125 HO₂ + 0.57 OH + 0.695 CH₃O₂ + 0.18 CH₃CHO
  +0.57 CO + acetaldehyde

2-methylpropene + O₃ → 0.41 HO₂ + 1.41RO₂ + 0.82 OH + 0.09 CH₂OO
  +0.41 CO + 0.5 CH₂O + 0.59 acetone

1-pentene + O₃ → 0.28 RO₂ + 0.18 OH + 0.12 CH₂OO + 0.18 CO + 0.5 CH₂O
  +0.1 propane + 0.62 Aldehyde

t2-pentene + O₃ → 0.125 HO₂ + 0.3475 RO₂ + 0.57 OH + 0.3475 CH₃O₂
  +0.09 CH₃CHO + 0.57 CO + 0.5 acetaldehyde
  +0.0625 ethane + 0.59 Aldehyde

c₂-pentene + O₃ → 0.125 HO₂ + 0.3475 RO₂ + 0.57 OH + 0.3475 CH₃O₂
  +0.09 CH₃CHO + 0.57 CO + 0.5 acetaldehyde
  +0.0625 ethane + 0.59 Aldehyde

2-methyl-1-butene + O₃ → 0.41 HO₂ + 0.41 RO₂ + 0.82 OH + 0.09 CH₂OO
  +0.41 CO + 0.5 CH₂O + 0.59 MEK

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3-methyl-1-butene + O₃ → 0.28 RO₂ + 0.18 OH + 0.18 CO + 0.5 CH₂O + 0.1 propane + 0.62 Aldehyde

1,3-butadiene + O₃ → 0.42 HO₂ + 0.08 OH + 0.12 CH₂OO + 0.67 CO + 0.5 CH₂O + 0.175 ethane + 0.62 Aldehyde

5 Cyclopentene + O₃ → RO₂
6 m-xylene + O₃ → RO₂
7 o-xylene + O₃ → RO₂
8 p-xylene + O₃ → RO₂
9 O₃ + hν → O¹D + O₂
10 NO₂ + hν + O₂ → NO + O₃
11 CH₃OOH + hν → OH + HO₂ + CH₂O
12 CH₃OOH + hν → HO₂ + CH₂O
13 ACO₃H + hν → OH + HO₂ + CO + CH₂O
14 C57OOH + hν → OH + HO₂ + Mgly + HOCH₂CHO
15 C58OOH + hν → OH + HO₂ + glyoxal + ACETOL
16 CH₃COCO₂H + hν → HO₂ + CH₃CO₃
17 CH₃NO₃ + hν → HO₂ + NO₂ + CH₂O
18 CH₃CO₃H + hν → OH + CH₃O₂

CO$_2$H$_3$CO$_3$H + hν → OH + HO$_2$ + glyoxal (A256)
CO$_2$H$_3$CO$_3$H + hν → HO$_2$ + CH$_3$CO$_3$ + HCOCO$_3$H (A257)
CO$_2$3C3CHO + hν → HO$_2$ + CH$_3$CO$_3$ + 2 CO (A258)
CO$_2$3C3CHO + hν → HCOCO$_3$ + CH$_3$CO$_3$ (A259)
CO$_2$H$_3$CHO + hν → 2 HO$_2$ + CO + HOCH$_2$CHO (A260)
HC$_4$ACO$_3$H + hν → OH + HO$_2$ + CO + ACETOL (A261)
HC$_4$ACOH + hν → 2 HO$_2$ + 2 CO + ACETOL (A262)
HC$_4$ACOH + hν → HO$_2$ + HC$_4$ACO$_3$ (A263)
HC$_4$CCO$_3$H + hν → OH + HOCH$_2$CHO (A264)
HC$_4$CCHO + hν → HO$_2$ + CH$_3$CO$_3$ + CO + HOCH$_2$CHO (A265)
HC$_4$CCHO + hν → HO$_2$ + HC$_4$CCO$_3$ (A266)
HCOCO$_2$H + hν → HO$_2$ + CO (A267)
HCOCO$_3$H + hν → OH + HO$_2$ + CO (A268)
HCOCO$_3$H + hν → OH + HO$_2$ + CH$_3$CO$_3$ + CO (A269)
HMVKAOOH + hν → OH + HO$_2$ + CH$_2$O + Mgly (A270)
HMVKBOOH + hν → OH + CH$_3$CO$_3$ + HOCH$_2$CHO (A271)
ISOPAOOH + hν → OH + HO$_2$ + HC$_4$CCHO (A272)
ISOPBOOH $+ \ h\nu \rightarrow \text{OH} + 0.75 \text{HO}_2 + 0.25 \text{CH}_3\text{O}_2 + 0.75 \text{CH}_2\text{O} + 0.75 \text{MVK} + 0.25 \text{MVKOH}$  

ISOPCOOH $+ \ h\nu \rightarrow \text{OH} + \text{HO}_2 + \text{HC}_4\text{ACCHO}$  

ISOPDOOH $+ \ h\nu \rightarrow \text{OH} + \text{HO}_2 + \text{CH}_2\text{O} + \text{MACR}$  

MACO$_3$H $+ \ h\nu \rightarrow \text{OH} + \text{CH}_3\text{CO}_3 + \text{CH}_2\text{O}$  

MACROOH $+ \ h\nu \rightarrow \text{OH} + \text{HO}_2 + \text{CH}_2\text{O} + \text{ACETOL}$  

MACROOH $+ \ h\nu \rightarrow \text{OH} + \text{HO}_2 + \text{CO} + \text{ACETOL}$  

MVKOOH $+ \ h\nu \rightarrow \text{OH} + \text{ACO}_3 + \text{CH}_2\text{O}$  

MVKOOH $+ \ h\nu \rightarrow \text{OH} + \text{ACO}_3 + \text{CH}_2\text{O} \text{A280}$  

MVKOH $+ \ h\nu \rightarrow \text{HO}_2 + \text{RCOO}_2 + \text{CO} + \text{CH}_2\text{O}$  

MVKOH $+ \ h\nu \rightarrow \text{CO}$  

MVK $+ \ h\nu \rightarrow \text{CO}$  

MVK $+ \ h\nu \rightarrow \text{HO}_2 + \text{CH}_3\text{CO}_3 + \text{CO} + \text{CH}_2\text{O}$  

MVK $+ \ h\nu \rightarrow \text{CO} + \text{propene}$  

MACR $+ \ h\nu \rightarrow \text{HO}_2 + \text{MACRO}_3$  

MACR $+ \ h\nu \rightarrow \text{HO}_2 + \text{CH}_3\text{CO}_3 + \text{CO} + \text{CH}_2\text{O}$  

MACROH $+ \ h\nu \rightarrow 2 \text{HO}_2 + \text{CO} + \text{ACETOL}$  

HOCH$_2$CHO $+ \ h\nu \rightarrow 2 \text{HO}_2 + \text{CO} + \text{CH}_2\text{O}$  

References
Glyoxal + $\nu \rightarrow 2 \text{HO}_2 + 2 \text{CO}$  \hspace{1cm} (A290)

Glyoxal + $\nu \rightarrow \text{CO} + \text{CH}_2\text{O}$  \hspace{1cm} (A291)

$\text{HO12C}_3\text{C4} + \nu \rightarrow \text{HO}_2 + \text{CH}_3\text{CO}_3$  \hspace{1cm} (A292)

$\text{HO12C}_3\text{C4} + \nu \rightarrow \text{HOCH}_2\text{CHO}$  \hspace{1cm} (A293)

$\text{HOCH}_2\text{COCHO} + \nu \rightarrow \text{HO}_2 + \text{CO}$  \hspace{1cm} (A294)

Isopa$\text{NO}_3 + \nu \rightarrow \text{HO}_2 + \text{NO}_2 + \text{HC}_4\text{CCHO}$  \hspace{1cm} (A295)

Isopb$\text{NO}_3 + \nu \rightarrow 0.75 \text{HO}_2 + 0.25 \text{CH}_3\text{O}_2 + \text{NO}_2 + 0.75 \text{CH}_2\text{O} + 0.75 \text{MVK}$
 + 0.25 MVKOH  \hspace{1cm} (A296)

Isopc$\text{NO}_3 + \nu \rightarrow \text{HO}_2 + \text{NO}_2 + \text{HC}_4\text{ACHO}$  \hspace{1cm} (A297)

Isopd$\text{NO}_3 + \nu \rightarrow \text{HO}_2 + \text{NO}_2 + \text{CH}_2\text{O} + \text{MACR}$  \hspace{1cm} (A298)

$\text{vglyox} + \nu \rightarrow \text{HO}_2 + \text{ACO}_3 + \text{CO}$  \hspace{1cm} (A299)

Acetaldehyde + $\nu \rightarrow \text{HO}_2 + \text{CH}_3\text{O}_2 + \text{CO}$  \hspace{1cm} (A300)

$\text{CH}_2\text{O} + \nu \rightarrow 2 \text{HO}_2 + \text{CO}$  \hspace{1cm} (A301)

$\text{CH}_2\text{O} + \nu \rightarrow \text{CO}$  \hspace{1cm} (A302)

Acetone + $\nu \rightarrow \text{CH}_3\text{O}_2 + \text{CH}_3\text{CO}_3$  \hspace{1cm} (A303)

Biacetoh + $\nu \rightarrow \text{RCOO}_2 + \text{CH}_3\text{CO}_3$  \hspace{1cm} (A304)

$\text{HCOC}_5 + \nu \rightarrow \text{RCOO}_2 + \text{CH}_3\text{CO}_3 + \text{CH}_2\text{O}$  \hspace{1cm} (A305)

$\text{mgly} + \nu \rightarrow \text{HO}_2 + \text{CH}_3\text{CO}_3 + \text{CO}$  \hspace{1cm} (A306)
acetol + hv → HO₂ + CH₃CO₃ + CH₂O  \hspace{1cm} \text{(A307)}

H₂O₂ + hv → 2 OH  \hspace{1cm} \text{(A308)}

RCOO₂NO₂ + M → RCOO₂ + NO₂ + M  \hspace{1cm} \text{(A309)}

GLYPAN + M → HCOCO₃ + NO₂ + M  \hspace{1cm} \text{(A310)}

MPAN + M → MACRO₃ + NO₂ + M  \hspace{1cm} \text{(A311)}

PAN + M → CH₃CO₃ + NO₂ + M  \hspace{1cm} \text{(A312)}

ACRPAN + M → ACO₃ + NO₂ + M  \hspace{1cm} \text{(A313)}

C₅PAN₁₉ + M → HC₄CCO₃ + NO₂ + M  \hspace{1cm} \text{(A314)}

C₅PAN₁₇ + M → HC₄ACO₃ + NO₂ + M  \hspace{1cm} \text{(A315)}

C₄PAN₆ + M → CO₂H₃CO₃ + NO₂ + M  \hspace{1cm} \text{(A316)}

C₄OH₂CPAN + M → C₄OH₂CO₃ + NO₂ + M  \hspace{1cm} \text{(A317)}

C₄PAN₅ + M → IPRHOCO₃ + NO₂ + M  \hspace{1cm} \text{(A318)}

O¹D + O₂ → O³P + O₂  \hspace{1cm} \text{(A319)}

O¹D + N₂ → O³P + N₂  \hspace{1cm} \text{(A320)}

O¹D + H₂O → 2OH  \hspace{1cm} \text{(A321)}

NO + HO₂ → NO₂ + OH  \hspace{1cm} \text{(A322)}

HO₂ + O₃ → OH + 2O₂  \hspace{1cm} \text{(A323)}

H₂O₂ + M → 2OH + M  \hspace{1cm} \text{(A324)}
\[\begin{align*}
H_2O_2 + OH & \rightarrow H_2O + HO_2 \\
OH + OH + M & \rightarrow H_2O_2 + M \\
HO_2 + HO_2 + M & \rightarrow H_2O_2 + O_2 + M \\
HO_2 + RO_2 + M & \rightarrow ROOH + O_2 + M \\
OH + NO_2 + M & \rightarrow HNO_3 + M \\
HO_2 + OH & \rightarrow H_2O + O_2 \\
OH + O_3 & \rightarrow HO_2 + O_2 \\
NO + RO_2 & \rightarrow 0.97 NO_2 + 0.97 HO_2 + 0.97 \text{ Aldehyde} + 0.03 \text{ RONO}_2 \\
OH + H_2O_2 & \rightarrow H_2O + HO_2 \\
RO_2 + RO_2 & \rightarrow HO_2 + \text{ Aldehyde} \\
RCOO_2 + RO_2 & \rightarrow HO_2 \\
RCOO_2 + NO_2 + M & \rightarrow PN \\
RCOO_2 + NO & \rightarrow NO_2 + \text{ Aldehyde} \\
NO + O_3 & \rightarrow NO_2 + O_2 \\
OH + \alpha \text{-pinene} + NO & \rightarrow 0.44 NO_2 \\
OH + \alpha \text{-pinene} + NO & \rightarrow 0.18 \text{ RONO}_2 \\
MVKOO + CO & \rightarrow MVK \\
MVKOO + NO & \rightarrow NO_2 + MVK
\end{align*}\]
MVKOO + H₂O → H₂O₂ + MVK  (A343)
MACROO + CO → MACR  (A344)
MACROO + NO → NO₂ + MACR  (A345)
MACROO + H₂O → H₂O₂ + MACR + MACO₂H  (A346)

MGLOO + CO → Mgly  (A347)
MGLOO + NO → NO₂ + Mgly  (A348)
MGLOO + H₂O → H₂O₂ + Mgly + CH₃COCO₂H  (A349)
GAOO + CO → HOCH₂CHO  (A350)
GAOO + NO → NO₂ + HOCH₂CHO  (A351)

GAOO + H₂O → H₂O₂ + HOCH₂CHO + HOCH₂CO₂H  (A352)
MGLYOO + CO → Mgly  (A353)
MGLYOO + NO → NO₂ + Mgly  (A354)
MGLYOO + H₂O → H₂O₂ + Mgly  (A355)
GLYOO + CO → glyoxal  (A356)

GLYOO + NO → NO₂ + glyoxal  (A357)
GLYOO + H₂O → H₂O₂ + glyoxal + HCOCO₂H  (A358)
ACLOO + CO → ACETOL  (A359)
ACLOO + NO → NO₂ + ACETOL  (A360)
Appendix B

Dilution and OH

The mixing term in Eq. (1) plays an important role in the processing of the Sacramento plume as it flows further downwind. This term is determined empirically with respect to hydrocarbon species measured both at Granite Bay and UC-BFRS.

ACLOO + H2O → H2O2 + ACETOL  
HMGLOO + CO → HOCH2COCHO  
HMGLOO + NO → NO2 + HOCH2COCHO  
HMGLOO + H2O → H2O2 + HOCH2COCHO  
MBOOO + CO → Ibitaloh  
MBOOO + NO → NO2 + Ibitaloh  
MBOOO + H2O → H2O2 + Ibitaloh + IPRHOOCO2H  
CH2OO + CO → CH2O  
CH2OO + NO → NO2 + CH2O  
CH2OO + H2O → CH2O + H2O2 + HCOOH  
CH3CHOO + CO → acetaldehyde  
CH3CHOO + NO → NO2 + acetaldehyde  
CH3CHOO + H2O → H2O2 + acetaldehyde + CH3CO2H  

(A361)  
(A362)  
(A363)  
(A364)  
(A365)  
(A366)  
(A367)  
(A368)  
(A369)  
(A370)  
(A371)  
(A372)  
(A373)
Dillon et al. (2002) estimated the dilution rate for the Sacramento urban plume to be 0.23 (±0.09) h⁻¹ based on a nonlinear least square optimization of the decay in the concentrations of VOCs. We find that this calculation leads to a dilution that is strongly anti-correlated with the effective OH. Dillon et al. (2002) also calculate the dilution into the Sierra Nevada using the HYSPLIT model obtaining a rate of dilution of 0.3 to 0.5 h⁻¹. Zaveri et al. (2003) estimated the rate of dilution in Nashville, Tennessee to be 0.11 h⁻¹ based on the rate at which the urban plume broadened downwind of the downtown area during the 1999 SOS campaign. Stickler et al. (2007) calculate rates of entrainment of free troposphere air into the planetary boundary layer of 0.01 to 0.15 h⁻¹. Kramp and Volz-Thomas (1997) calculate values in the range of 0.20 to 0.43 h⁻¹ in the region of Freiburg, Germany. There is broad consistency in these values.

Equation (1), which describes the change in concentration of a compound X with time, can be simplified to:

\[ \frac{d[X]}{dt} = -k_d ([X] - [X]_{bg}) - k_{OH+X} [X][OH] \]  

(B1)

for hydrocarbons that have negligible photochemical production, emission and deposition throughout the transect. The term \( k_d ([X] - [X]_{bg}) \) in Eq. (B1) represents the entrainment of background air with concentration \([X]_{bg}\) at a rate of \( k_d \). The term \( k_{OH+X} [X][OH] \) represents the photochemical loss of \( X \) as it reacts with \( OH \) with rate \( k_{OH+X} \). Concentrations of \( X \) as a function of time are obtained by integrating (B1) numerically. Following Dillon et al. (Dillon et al., 2002), we determine \( k_d \) and \( OH \) by nonlinear least squares fit of Eq. (B1) using various hydrocarbons observations at Granite Bay and UC-BFRS.

We use 9 hydrocarbons with lifetimes ranging from 1 to 6.5 d at an OH concentration of \( 3 \times 10^6 \) molecules cm⁻³. Table B1 shows the concentration of these species at Granite Bay, at UC-BFRS. The concentrations of hydrocarbons of anthropogenic origin observed at UC-BFRS during weekdays spans from 20% to almost 90% of what is observed at Granite Bay 5 h earlier, with the highest conserved fraction observed for benzene which has the longest photochemical lifetime.
We define two different background scenarios, the GLOBAL\textsubscript{bg} and LOCAL\textsubscript{bg}. The GLOBAL\textsubscript{bg} is an estimate of free troposphere air in the region based on observations made during the summer of 2007 in the region from an airplane platform during the TC4 campaign and is representative of a low global background. The LOCAL\textsubscript{bg} takes advantage of measurements made at Big Hill that are characteristic of the free troposphere air (Murphy et al., 2006a) and is representative of a high local background. A more detailed description of the background definitions is presented in Appendix C.

We obtain a $k_d$ of $0.24\pm0.06$ h\textsuperscript{-1} and an average OH of $8\pm3\times10^6$ molecules cm\textsuperscript{-3} for the GLOBAL\textsubscript{bg} case and a $k_d$ of $0.4\pm0.1$ h\textsuperscript{-1} and an average OH of $5\pm4\times10^6$ molecules cm\textsuperscript{-3} for the LOCAL\textsubscript{bg} scenario. Dillon et al. (2002) obtain a $k_d$ of $0.23\pm0.09$ h\textsuperscript{-1} and an OH of $1.1\pm0.5\times10^7$ molecules cm\textsuperscript{-3}. The differences are due to both the variation in the VOC used and to the background values.

If instead of a fixed OH we allow OH to vary along the transect based on the fully couple model, the optimization leads to a value of $k_d$ of $0.43$ h\textsuperscript{-1} for LOCAL\textsubscript{bg} and of $0.31$ h\textsuperscript{-1} for GLOBAL\textsubscript{bg} and an average OH of $4.6\times10^6$ molecules cm\textsuperscript{-3} and $5.0\times10^6$ molecules cm\textsuperscript{-3} for the LOCAL\textsubscript{bg} and the GLOBAL\textsubscript{bg}, respectively. The spread in these values gives a sense of how the choice of background concentrations affects the dilution and OH derived. The decrease in concentration of VOCs due to entrainment of background air ranges from 60% to 85% in the different scenarios.

**Appendix C**

**Definition of background air**

As described by Murphy et al. (2006a), on an average summer day, an airmass moves roughly 100 km from east to west during the daytime and then backtracks approximately 50 km to the west during the night when the flow is reversed. This pattern results in air sloshing back and forth along the western slopes of the Sierra and con-
tributes to an increase in the regional background of species of anthropogenic origin as the week progresses. Because of this behavior, the regional background of species with anthropogenic influence is hard to define. The vertical and horizontal distribution of species in the area, depicted for ozone by Carroll and Dixon (2002), adds to the difficulty in defining the regional background. They find significant variation in ozone at a horizontal scale of a few kilometers and vertical layering above the mixed layer.

As described before, the 0-D representation of the plume is most characteristic of the center line of the plume where vertical mixing dominates. Vertical mixing is characterized by entrainment of free troposphere air from aloft. We describe two possible scenarios for estimating free troposphere concentrations of species that are influenced by anthropogenic emissions. For one estimate of free troposphere air in the region, we use observations made during the summer of 2007 in the region from an airplane platform during the TC4 campaign (TC4 Data Archive, 2009). This definition of a background airmass is representative of a low global background and is used in the Reference scenario. The second method takes advantage of measurements made at Big Hill that are characteristic of the free troposphere air. This second definition of a background airmass results in higher values. The VOC GLOBAL\(_{bg}\) is approximately 40% of the VOC LOCAL\(_{bg}\). The nitrogen oxides LOCAL\(_{bg}\) is similar to the GLOBAL\(_{bg}\). The GLOBAL\(_{bg}\) concentration of species not measured during TC4 is estimated to be 40% of their LOCAL\(_{bg}\) value.

Definition of the high local background is based on observations of NO\(_2\), \(\Sigma\)PNs, \(\Sigma\)ANs and HNO\(_3\) as well as meteorological parameters and O\(_3\) that were made during the summer of 2003 at Big Hill (38.84° N, 120.41° W, 1860 m) approximately 20 km southeast of UC-BFRS. These measurements, which are described in detail by Murphy et al. (2006a), show influence by the free troposphere during some nights. Regional background concentrations for NO\(_2\), HNO\(_3\), \(\Sigma\)PNs, \(\Sigma\)ANs and O\(_3\) are estimated based on plots of the species vs. [H\(_2\)O] for nights that show influence by free troposphere air. Background concentrations for anthropogenic VOCs are determined based on the linear regression of their plots vs. \(\Sigma\)NO\(_{y,i}\) (\(\Sigma\)NO\(_{y,i}\)=NO\(_2\)+\(\Sigma\)PNs+\(\Sigma\)ANs+HNO\(_3\)) at
UC-BFRS for nighttime data, if observations are available, or at Granite Bay. This background will be referred to LOCAL$_{bg}$.

Table B1 (in Appendix B) presents the observations at Granite Bay (GB) and UC-BFRS and compares the model outputs of hydrocarbons that are used to fit the rate of entrainment with UC-BFRS observations for both LOCAL$_{bg}$ and GLOBAL$_{bg}$. As mentioned before, the rate of entrainment calculated for the LOCAL$_{bg}$ scenario is 0.43 h$^{-1}$ while the rate of entrainment for the GLOBAL$_{bg}$ scenario is 0.31 h$^{-1}$. The background concentrations for these species for both background scenarios are also included in the table. As mentioned before, the LOCAL$_{bg}$ concentrations for VOCs are higher than the GLOBAL$_{bg}$ concentrations. As $k_d$ is calculated based on background concentrations, the outputs are comparable for most anthropogenic VOCs for both background definitions. Most are within 20% of the observed value except for isopentane and toluene in the GLOBAL$_{bg}$ scenario, both of which are within 25% of the observations. An exception is benzene for which the calculated outputs are significantly different in both cases. Although we cannot explain this difference, one possible explanation is that the regional background of benzene has decreased between 2001, the year the data was collected at GB and UC-BFRS, and 2007, the year during which the TC4 data was obtained. Harley et al. (2006) show that the benzene concentration has steadily decreased between 2001 and 2004 in the San Francisco Bay area indicating that it is not unlikely that the same has occurred in the Sacramento area and downwind.

Neither of the two estimates presented above are adequate to describe the characteristic mixing ratios in the free troposphere of species that are direct biogenic emissions or products of the oxidation of these emitted species. Species that are influenced by biogenic emissions or by oxidation of biogenic VOCs can have background concentrations that are hard to define because they can reach higher concentrations at night, the period during which the LOCAL$_{bg}$ is defined. These species included isoprene, MBO, $\alpha$-pinene, which are directly emitted by vegetation, and MVK, MACR and acetaldehyde which are produced in the oxidation process of isoprene. Additionally, acetaldehyde, acetone, ethanol and methanol are all oxygenated VOCs that have
been shown to have upward fluxes at UC-BFRS (Schade and Goldstein, 2001) and thus also have hard to define backgrounds. Background concentrations of species affected by biogenic emissions are based on the lowest observed values at UC-BFRS when observations are available. Background concentrations for species that are not routinely monitored like many of the larger organic peroxides and acids formed from isoprene oxidation are assumed to be zero. Background concentrations of glycoaldehyde, hydroxyacetone, glyoxal and methylglyoxal are assumed to be 50% of the means value observed by Spaulding et al. (2003) at UC-BFRS. Background concentrations of hydrogen peroxide, methyl hydroperoxide, and formaldehyde are taken from observations over North America between 1 and 6 km during INTEX-A (Snow et al., 2007). The background concentrations for these species are the same for both the LOCAL_{bg} and the GLOBAL_{bg} scenarios and setting them to zero does not lead to significant differences in the model results.

The different background concentrations were used to test the sensitivity of the model to background concentrations and rates of entrainment as described in the previous section. The GLOBAL_{bg} scenario was used as the Reference case scenario for testing the sensitivity of other parameters in the model.

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Nitrogen oxide chemistry in an urban plume

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Table 1. Initial values for the base case (ppb).

<table>
<thead>
<tr>
<th>Species</th>
<th>Initial value</th>
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<td>Acetaldehyde</td>
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</tr>
<tr>
<td>Acetone</td>
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</tr>
<tr>
<td>terpenes</td>
<td>0.013±0.009+0.0008 a</td>
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<tr>
<td>Benzene</td>
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<td>Butane</td>
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<tr>
<td>1,3-butadiene</td>
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a α-pinene + limonene + 3-carene
### Table 2. Summary of model results for various scenarios.

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<th>ANs \textsubscript{2}</th>
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<th>ANs \textsubscript{5}</th>
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<th>Obs.</th>
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<td>Ref.</td>
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<td>% Diff</td>
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<td>–14.9</td>
<td>2832</td>
<td>–19.5</td>
<td>2944</td>
<td>–14.9</td>
<td>2953</td>
<td>–14.6</td>
<td>2996</td>
<td>–12.9</td>
<td>3012</td>
<td>–12.3</td>
</tr>
<tr>
<td>O\textsubscript{3} (ppbv)</td>
<td>72.6</td>
<td>–0.6</td>
<td>72.4</td>
<td>–0.8</td>
<td>72.5</td>
<td>–0.7</td>
<td>73</td>
<td>0.0</td>
<td>73.3</td>
<td>0.4</td>
<td>73.2</td>
<td>0.3</td>
</tr>
<tr>
<td>NO\textsubscript{eq}/NO\textsubscript{eq}</td>
<td>0.249</td>
<td>–2.4</td>
<td>0.232</td>
<td>–9.9</td>
<td>0.249</td>
<td>–2.4</td>
<td>0.253</td>
<td>–0.8</td>
<td>0.277</td>
<td>7.9</td>
<td>0.288</td>
<td>11.5</td>
</tr>
<tr>
<td>NO\textsubscript{eq}/NO\textsubscript{eq}</td>
<td>0.320</td>
<td>–3.0</td>
<td>0.302</td>
<td>–13.2</td>
<td>0.331</td>
<td>–3.3</td>
<td>0.339</td>
<td>–0.9</td>
<td>0.383</td>
<td>10.7</td>
<td>0.405</td>
<td>15.6</td>
</tr>
<tr>
<td>PN\textsubscript{eq}/NO\textsubscript{eq}</td>
<td>1.052</td>
<td>–3.6</td>
<td>1.148</td>
<td>5.1</td>
<td>1.045</td>
<td>–4.2</td>
<td>1.082</td>
<td>–0.7</td>
<td>0.994</td>
<td>–9.6</td>
<td>0.940</td>
<td>–15.9</td>
</tr>
<tr>
<td>ANs \textsubscript{5}/NO\textsubscript{eq}</td>
<td>0.522</td>
<td>–13.3</td>
<td>0.578</td>
<td>–2.2</td>
<td>0.538</td>
<td>–9.8</td>
<td>0.433</td>
<td>–36.4</td>
<td>0.269</td>
<td>–104.4</td>
<td>0.264</td>
<td>–123.7</td>
</tr>
<tr>
<td>HNO\textsubscript{3}/NO\textsubscript{eq}</td>
<td>1.439</td>
<td>13.8</td>
<td>1.584</td>
<td>21.7</td>
<td>1.439</td>
<td>13.8</td>
<td>1.434</td>
<td>13.6</td>
<td>1.328</td>
<td>6.6</td>
<td>1.279</td>
<td>3.1</td>
</tr>
</tbody>
</table>

- **a** soil NO emission flux (ppt m s\textsuperscript{-1})
- **b** effective isoprene nitrate lifetime (hours) to Reaction (R4b)
- **c** all concentrations are pptv unless otherwise noted
- **d** % difference between model and observations, calculated as 100\%\times (Model-Observed)/(Model)
- **e** modified PNs scenario described in Sect. 4.3
- **f** revised model featuring changes to PNs and ANs chemistry
Table 3. Table B1. Hydrocarbons observations (ppb) used to fit the rate of entrainment of background air, background air concentrations (ppb), the lifetime to OH assuming a 12 h average OH of $3 \times 10^6$ molecules cm$^{-3}$ (days) and outputs (ppb) for the different background definitions. All concentrations are in ppb.

<table>
<thead>
<tr>
<th>Species</th>
<th>$\tau_{OH}$ (days)</th>
<th>Obs. at GB</th>
<th>Obs. at UC-BFRS</th>
<th>LOCAL$_{bg}$</th>
<th>GLOBAL$_{bg}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Bg</td>
<td>Model</td>
<td>% dif.</td>
<td>Bg</td>
</tr>
<tr>
<td>benzene</td>
<td>6.53</td>
<td>0.097</td>
<td>0.085</td>
<td>0.075</td>
<td>0.083</td>
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<tr>
<td>n-butane</td>
<td>3.04</td>
<td>0.28</td>
<td>0.083</td>
<td>0.073</td>
<td>0.093</td>
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<tr>
<td>ethyl benzene</td>
<td>1.03</td>
<td>0.043</td>
<td>0.010</td>
<td>0.010</td>
<td>0.010</td>
</tr>
<tr>
<td>hexane</td>
<td>1.48</td>
<td>0.075</td>
<td>0.015</td>
<td>0.010</td>
<td>0.016</td>
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<tr>
<td>i-butane</td>
<td>3.32</td>
<td>0.17</td>
<td>0.060</td>
<td>0.045</td>
<td>0.060</td>
</tr>
<tr>
<td>i-pentane</td>
<td>1.98</td>
<td>0.50</td>
<td>0.12</td>
<td>0.080</td>
<td>0.11</td>
</tr>
<tr>
<td>methyl pentanes</td>
<td>1.48</td>
<td>0.23</td>
<td>0.050</td>
<td>0.030</td>
<td>0.050</td>
</tr>
<tr>
<td>n-pentane</td>
<td>2.35</td>
<td>0.18</td>
<td>0.050</td>
<td>0.037</td>
<td>0.050</td>
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<tr>
<td>Toluene</td>
<td>1.25</td>
<td>0.29</td>
<td>0.065</td>
<td>0.050</td>
<td>0.062</td>
</tr>
</tbody>
</table>

*a % dif. = 100 x (Model - Observation / Model)
Fig. 1. Map of study region, with prevailing day time wind pattern shown.
Fig. 2. Comparison of modeled and observed NO$_y$ partitioning at UC-BFRS.
**Fig. 3.** Time evolution of NO\textsubscript{y} species. UC-BFRS observations indicated by black circle.
Fig. 4. Time evolution of ΣPNs and their major individual PNs. Other speciated PNs include the sum of ACRPAN, C5PAN17, C5PAN19, C4OH2CPAN, C4PAN6 and GLYPAN (as referred to by MCM). UC-BFRS observations indicated by black circle. (a) Reference model (b) modified PNs chemistry model scenario.
Fig. 4. Continued.
Fig. 5. Time evolution of $\Sigma$ANs and of the major classes of ANs. Other speciated ANs included the sum of C58NO$_3$, CH3NO$_3$, HMVKANO$_3$ (as referred to by MCM) and aromaticNO$_3$, which includes alkyl nitrates derived from toluene, ethyl benzene, $m$-xylene, $o$-xylene and $p$-xylene. UC-BFRS observations indicated by black circle.