The reaction of hydroxyl and methylperoxy radicals is not a major source of atmospheric methanol

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Methanol is a benchmark for understanding tropospheric oxidation, but is underpredicted by up to 100% in atmospheric models. Recent work has suggested this discrepancy can be reconciled by the rapid reaction of hydroxyl and methylperoxy radicals with a methanol branching fraction of 30%. However, for fractions below 15%, methanol underprediction is exacerbated. Theoretical investigations of this reaction are challenging because of intersystem crossing between singlet and triplet surfaces ~45% of reaction products are obtained via intersystem crossing of a pre-product complex – which demands experimental determinations of product branching. Here we report direct measurements of methanol from this reaction. A branching fraction below 15% is established, consequently highlighting a large gap in the understanding of global methanol sources. These results support the recent high-level theoretical work and substantially reduce its uncertainties.
The hydroxyl radical, OH, sometimes called the tropospheric detergent, is an essential oxidant in Earth’s lower atmosphere. In the absence of substantial anthropogenic contributions, dominant atmospheric sinks of OH are reactions with CO and CH₄. The reaction of OH with CH₄ (1) yields the simplest and most abundant atmospheric alkylperoxy radical, methylperoxy (CH₃OO)₃

\[
\text{OH} + \text{CH}_4(\text{+O}_2) \rightarrow \text{CH}_3\text{OO} + \text{H}_2\text{O} \tag{1}
\]

Steady-state concentrations of methylperoxy range between 1–20 ppt; atmospheric sinks include reaction with NO, HO₂, and self- and cross-reactions with other peroxy radical species. The latter reactions lead to methanol production of 48 teragrams (Tg) per year and are consequently an important source of atmospheric methanol, in particular over remote regions where primary emission sources, such as plant growth, plant decay, and anthropogenic sources are negligible.

Methanol concentrations range from 1–15 ppbv in the continental boundary layer and 0.1–1 ppbv in the remote troposphere. Oxidation of methanol forms species including CO, formaldehyde, and tropospheric ozone, and reactions of alcohols may have subtle, indirect effects in the formation of secondary organic aerosols, therefore impacting the tropospheric oxidising capacity, air quality and human health. Atmospheric methanol abundances are dominated by direct emissions but sources also include oxidation pathways of methane and other volatile organic species. Methanol is thus a benchmark for the performance of atmospheric models. Despite inclusion of multiple methanol production pathways, global atmospheric methanol, in particular over remote regions, and so other production pathways have been sought.

Until recently, the coupling between OH and CH₃OO had not been investigated, despite the large rate coefficient recommended by Tsang and Hampson (k = 1 × 10⁻¹⁰ cm³ s⁻¹) and the suggestion that a major product would be methanol (CH₃OH). Four likely product channels exist:

\[
\begin{align*}
\text{CH}_3\text{OO} + \text{OH} & \rightarrow \text{CH}_2\text{O} + \text{HO}_2 & \tag{2} \\
\text{CH}_3\text{OO} + \text{OH} & \rightarrow \text{CH}_2\text{OO} + \text{H}_2\text{O} & \tag{3} \\
\text{CH}_3\text{OO} + \text{OH} & \rightarrow \text{CH}_3\text{OH} + \text{O}_2 & \tag{4} \\
\text{CH}_3\text{OO} + \text{OH}(+\text{M}) & \rightarrow \text{CH}_3\text{OOOH}(+\text{M}) & \tag{5}
\end{align*}
\]

Recent experiments established a high rate coefficient for reactions of OH with methyloxy (CH₃OO), between 1–2 × 10⁻¹⁰ cm³ s⁻¹, with similar rate coefficients for larger alkylperoxy radicals. The branching fractions for the product channels of the OH + CH₃OO reaction have been estimated through theoretical approaches by Müller et al., and channels (2) and (3) probed experimentally by Yan et al. and Assaf et al.

To date, no experimental studies have directly measured ϕ(CH₃OH).

Substantial mechanistic insight into this reaction is given by the high-level ab initio calculations in Müller et al., which characterise key stationary points on the reaction potential energy surface including the three bimolecular product channels (2–4), the trioxide association product (CH₃OOO)(5) and a pre-product complex. Müller et al. ascertained product branching ratios through RRKM calculations, which, notably, identify triplet entrance routes as "entirely negligible," and show the dominance of the singlet trioxide intermediate, which can rapidly convert to the pre-product complex (CH₃O...HOO), which has only a 40 ps lifetime at its initial energies. The coupling via intersystem crossing (ISC) of the singlet and triplet states of the product complex affects the product branching. The singlet state primarily undergoes rapid H-bond scission to yield bimolecular products CH₃OH + HO₂ (2) with a small (~5%) component dissociating to CH₃OH and O₂ (Σg⁻). The triplet state has competing pathways: direct and indirect CH₃OO + HO₂ production (the latter via ISC back to the singlet state) or rearrangement and subsequent decomposition to CH₃OH + O₂ (Σg⁻). The multiple favourable routes to (2) serve to facilitate high yields of HO₂ and CH₃O; branching from the triplet state of the pre-product complex to methanol (4) is calculated to be about twice as favourable (~10%) as its formation from the singlet surface. However, Müller et al. estimated that the uncertainty in the stationary point energies and in the ISC probability gave uncertainties of a factor of 3.5 in the branching fractions. Dramatically different tropospheric effects are encompassed by the upper and lower limits of the methanol yield, ϕ(CH₃OH), given by Assaf et al. (0–40%), Müller et al. (2–30%) and Ferracci et al. (0–40%).

The potential importance of this reaction, especially in the remote troposphere, was noted by Archibald et al. based on box model analysis and was built on by Fittschens et al. using data from the remote Cape Verde Observatory. Khan et al. included this reaction in a global model and noted the importance of this reaction with respect to background methanol if the channel (4) forming methanol were significant. Recent studies (Müller et al., Khan et al., and Ferracci et al.) suggest that a large ϕ(CH₃OH) would dramatically change methanol levels. Applying a yield of 0% for (4) within a global chemical transport model, Müller et al. find that the discrepancy between modelled and measured atmospheric methanol is significantly exacerbated, owing to the loss of CH₃OO through reaction with OH, rather than the self-reaction, which yields CH₃OH. Only with a yield of 30% for (4) were Müller et al. able to reconcile measured and modelled methanol.

The existing error bounds on the methanol yield, therefore, leave uncertainties not merely on the magnitude but even on the direction of the impact of this reaction, which highlights the need for direct experimental quantification of the yield. Ferracci et al. argue that the total rate coefficient indicated by the most recent determinations, lower than that used by Müller et al. would place even more stringent requirements on the methanol yield needed to improve model-measurement agreement; the yield of (4) would need to be in excess of 0.8 to reconcile modelled and measured methanol abundances. We report direct determinations of the methanol yield using two different experimental approaches: isotopologues of OH + CH₃OO via multiplexed photoionization mass spectrometry (MPIMS) and a chamber study coupled to proton-transfer reaction time-of-flight mass spectrometry (PTR-TOFMS).

Results

**Pulsed photolysis MPIMS experiments.** The products of the OH + CH₃OO reaction were quantified at 30 Torr in pulsed photolysis experiments using the Sandia multiplexed photoionization mass spectrometer, and at 740 Torr using a new high-pressure reactor, both interfaced with the tuneable-VUV-output of the Chemical Dynamics Beamline (9.0.2) at the Advanced Light Source of Lawrence Berkeley National Laboratory (see the Methods section for further details). At 30 Torr methylperoxy radicals were produced by photolysis of ¹³CH₂I (to move the methanol mass away from ⁵²O₂ background) in the presence of a large excess of O₃, and OH was produced by photolysis of H₂O₂. In the 740 Torr experiment, reactions of F-atom (generated by
photolysis of XeF₂\(^+\) with CH₃ and D₂O produced CH₃ and OD in the presence of O₂. Photoionization mass spectrometry detects precursors, intermediates, and products. Primary and secondary reaction products were observed, including HCHO, HO₂, and methanol, confirmed by their photoionization spectra (see Supplementary Figs. 4, 5). Known photoionization cross-sections are used to quantify reactant (H₂O₂, D₂O) and product concentrations in the photoionization measurements (see Supplementary Note 1 and Figures therein). The competition between CH₃OO self-reaction and reaction with OH was assessed through a chemical kinetic model (see Supplementary Note 2, Tables and Figures therein). Figure 1 illustrates the relative contribution of CH₃OO self-reaction to methanol production for representative experiments with and without H₂O₂; the data clearly show an additional source of methanol upon addition of H₂O₂, which can be attributed to reactions of CH₃O with HO₂ and branching to channel (4). No evidence is found for the formation of the Criegee intermediate (reaction 3), consistent with the upper limit of 5% reported elsewhere.

The observed product concentrations were compared to a kinetic model including the OH + CH₃OO reaction, with the branching fraction of CH₃OH from the OH + CH₃OO reaction as a fitted parameter (Supplementary Note 2). Absolute concentration determinations as shown in Fig. 1a display significant sensitivity to the absolute concentration calibration and photolytic depletion. Because photoionization cross-sections of methanol, formaldehyde and H₂O₂ are better-known from the measurements of Dodson et al. than are the absolute cross-sections, the most reliable determination of the branching rests on a quantification of the ratio of formaldehyde to methanol. Moreover, because in this reaction system formaldehyde and methanol principally have common sources, the ratio of concentrations normalises for many factors and provides dramatically reduced parametric sensitivity, as can be seen in Supplementary Fig. 3 for the same data set. The dominant uncertainty (see Supplementary Note 4, Tables and Figures therein) is the ± 15% uncertainty in the relative cross-sections for formaldehyde and methanol, with smaller uncertainties from the rate coefficient for CH₃O with HO₂ and for I atom with HO₂.

Propagated uncertainties in the total rate coefficient for the reaction of OH + CH₃OO, in the absolute concentration calibration, and in the photolysis fraction used to initialise the simulation are insignificant contributors to uncertainty in the branching fraction. We derive a methanol branching fraction of 9 \(±\) 5% (assuming negligible branching to (3) and (5)) from a series of six measurements of the CH₃OO + OH reaction. Figure 2 shows results for a representative measurement. Observations of a small methanol yield strongly support the theoretical value (~7%) for \(\phi_{\text{CH₃OH}}\) from Müller et al.

The calculations by Müller et al. also showed that at increased pressures, a greater fraction of the trioxide association product (5) is stabilised, predicting a trioxide fraction of approximately 11% at ~1 atm total pressure (c.f. ~0.02% at 30 Torr), at the expense of bimolecular product channels. We find significant evidence for the stabilisation of the trioxide at 740 Torr, but not at total pressures ≤ 30 Torr, consistent with the calculations of Müller et al. (see Supplementary Note 6 and Figures therein). We are unable to determine an absolute experimental yield for the trioxide, as the photoionization cross-section is unknown. However, assuming that the trioxide photoionization cross-section is comparable to that of methanol would give a yield in the range ~3–12% at 740 Torr (using He bath gas). This is consistent with the 9.6% value calculated for the same pressure (where the bath gas is air) from the expression of Müller et al.

The experiment at 740 Torr is designed so that the ratio of CH₃O to CH₃OD in this system is highly sensitive only to the branching ratio (k₂/k₄), and insensitive to photolysis fraction or overall rate coefficients. Analysis returns \(\phi_{\text{CH₃OH}} = (6 ± 2)\%\) (see Fig. 2b), indicating, even allowing for a possible kinetic isotope effect, at most a weak negative pressure dependence in the methanol branching fraction, consistent with calculations.

Continuous photolysis chamber experiments. Reactions were also carried out at atmospheric pressure in a 300 L Teflon bag, using different detection techniques (connected to a PTR-TOFMS and an O₃ analyser through Teflon tubing) and generation of the
reactants. Oxygen (1D, 3P) atoms were formed by 254 nm photolysis of O₃ in the presence of CH₄ and H₂O at 760 Torr of synthetic air, producing OH radicals (further details in Supplementary Note 3). The OH formed CH₃OO through reaction (1), which after a few seconds reached a steady-state concentration (same as HO₂, blue open squares and blue solid diamonds, Fig. 3b) at a level where its reaction rate with OH was competitive with the reaction rate of OH with CH₄. The profiles in Fig. 3 were modelled (Supplementary Figs. 6, 7) with the O₃ photolysis rate and ϕ(CH₃OH) as the only adjustable parameters. Reaction conditions and depletions were chosen such that the reaction of CH₃OO with OH remained the major source for CH₃OH (dashed line) at its parent protonated mass (CH₅O₃⁺). We have undertaken preliminary ab initio calculations that demonstrate that even if trioxide survives the sampling, it may be detected as protonated methanol (Supplementary Note 3). Two protonation sites are energetically feasible, α and γ with respect to the methyl group. The γ-protonated trioxide is unstable and fragments to H₂O + CH₂O⁺. The α-protonated trioxide is thermodynamically unstable even relative to O₂ + CH₃O⁺. Direct dissociation of the bare cation (CH₅O⁺) has a barrier, but there is a barrierless water-catalysed dissociation pathway (Supplementary Fig. 12). H₂O is present in close proximity to the newly protonated trioxide as a result of the proton-transfer reaction in the PTR-TOFMS detection system and is also present.
in appreciable concentrations as a reaction precursor (2.5 – 3.8 \times 10^{16} \text{ molecule cm}^{-2} and higher in the PTR-TOFMS chamber due to the injection of water to produce H_2O_2). It is, therefore, likely that the appreciable yield of trioxide stabilised at the higher pressures of the chamber experiments will lead to additional signal at the protonated methanol mass, resulting in artificially enhanced methanol yields in the chamber experiments. Because there is no method for calibrating the PTR-TOFMS for trioxide, the degree of interference cannot be directly determined.

**Atmospheric model.** To determine the effect of the OH + CH_3OO reaction and its branching on tropospheric composition, we compared a STOCHEM-CRI model that included the title reaction (total rate coefficient from Assaf et al.\(^{15}\)) and \(\Phi_{\text{CH}_3\text{OH}} = 7\%\) to a base case integration that omitted it. This base case scenario is in accordance with other studies\(^{18}\) that isolate the effect of the OH + CH_3OO reaction; any assignment of \(\Phi_{\text{CH}_3\text{OH}}\) would serve to change predicted CH_3OH, H_2O_3, or products of CH_3OO reactions. Compared to the base case, addition of the OH + CH_3OO reaction with the \(\Phi_{\text{CH}_3\text{OH}} = 7\%\) made only small changes to the global burdens of OH (−0.9%), CO (+1.0%), O_3 (−1.3%), CH_3OH (−1.7%) and HCHO (−0.6%) (where the values given in parenthesis are the average values for all grid bases) but had a substantial impact on the global burdens of H_2O (7%), CH_3OO (−19.6%), CH_3OOH (−11.7%) and other alkyl hydroperoxides (ROOH) (+4.8). The OH + CH_3OO reaction decreases CH_3OO (−19.6%) because of removal via reaction with OH and increases the production flux of H_2O_3 through reaction 2 and thereby increases the production of other ROOH. Simultaneously, reaction 4 increases the net production flux of methanol by only 3 Tg/yr from the base case scenario, with 28.7 Tg/yr obtained from peroxy radical reactions (within the range of previous estimates of 15 – 38 Tg/yr)\(^{18,22}\).

However, a \(\Phi_{\text{CH}_3\text{OH}}\) of 17% (corresponding to the yield from the chamber experiments of this study, uncorrected for the trioxide interference, see Supplementary Fig. 17) increases the global burden of methanol by 14% from the base case scenario, which is lower than the study of Ferracci et al.\(^{20}\), which found 36% increment of methanol abundances with \(\Phi_{\text{CH}_3\text{OH}}\) of 20% from the scenario with \(\Phi_{\text{CH}_3\text{OH}}\) of 0%. Under these assumptions methanol production is found to be 54.3 Tg/yr, compared to 116.7 Tg/yr (direct production of 66.1 Tg/yr and indirect production through trioxide formation of 50.6 Tg/yr) estimated for \(\Phi_{\text{CH}_3\text{OH}} = 30\%\) by Müller et al.\(^{18}\).

To reconcile modelled and measured methanol abundances, Müller et al.\(^{18}\) utilised a yield of 30% for reaction (2c), the upper limit of their calculated range and also the higher rate coefficient\(^{22}\), \(k = 2.8 \times 10^{-10} \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}\). However, Ferracci et al.\(^{20}\) used \(k = 1.6 \times 10^{-10} \text{ cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}\) in their modelling study and found comparatively lower CH_3OH production (60 Tg/yr) using the yield of 40%, suggesting that a far higher yield would be needed to reconcile models with measurements. The experimental data presented herein demonstrates that the branching fraction at 298 K is instead closer to the calculated value of \(\approx 7\%\) producing only 22.4 Tg/yr methanol, which is smaller than required to rationalise atmospheric observations.

The spatially resolved changes in annual surface levels, compared with the base case integration, are shown in Fig. 4 and discussed in detail in Supplementary Discussion 1. Modest impact is observed on the abundances of OH (−8%), O_3 (−4%), CO (+2.5%) and HCHO (−2.5%), and significant changes are observed for HO_2 (+25%), CH_3OOH (−18%) and ROOH (+40%) (where the values stated in parenthesis are the maximum changes obtained). Increases in CH_3OH are found over terrestrial locations, but substantial reductions of up to 30% are estimated in remote tropical regions. Here, the reduction in CH_3OO due to its reaction with OH has retarded the in-situ production of CH_3OH through the self-reaction of CH_3OO and its cross-reactions with other peroxy radicals at remote sites\(^{33}\). Therefore, rather than provide a new source of remote CH_3OH, with a \(< 7\%\) yield of 2(c), inclusion of the OH + CH_3OO reaction exacerbates the under-estimation of remote CH_3OH.

Further integrations with different methanol yields ranging from 0.1 to 1 from OH + CH_3OO (Fig. 5) show that the reaction can be a significant source of methanol over tropical oceans only when \(\Phi_{\text{CH}_3\text{OH}}\) is higher than 0.15, consistent with other results\(^{18,20}\), which can be considered to be the compensation point when reaction (4) can begin to contribute to tropospheric CH_3OH over remote tropical oceans. Using the experimentally determined methanol branching fraction of 6%–9% would lead to a significant decrease in atmospheric methanol, specifically in remote regions.

Figure 6 shows a model comparison with a representative data set, also used in earlier comparisons\(^{18}\), which shows that the reaction 4 has little impact on modelled CH_3OH level over mid-latitude tropical oceanic areas (e.g., Atlantic, Pacific). Müller et al.\(^{18}\) use a fraction of 0.65 for tropospheric conversion of trioxide to CH_3OH, assuming gas-phase release of methanol from the condensed phase. However a peak fraction of only about 0.2 (centred above the tropical oceans) is predicted to directly produce gas-phase methanol, with most trioxide removed by wet deposition (and condensed phase formation of CH_3OH)\(^{18}\). Assuming 65% conversion of trioxide to methanol, in addition to our experimentally determined methanol yield of 6–9%, leads to an effective yield around the compensation point of 15.5%.

**Discussion**

The yield of methanol determined experimentally here for the cross-reaction of two important oxidants, OH and CH_3OO, agrees with the small methanol production predicted by Müller et al.\(^{18}\). In their calculations, the constrained nature of the transition state to hydrogen transfer leads to a preference for direct scission of the pre-product complex to the H_2O_3 and CH_3O products over methanol formation on both the singlet and triplet surfaces. The present results confirm this preference for CH_3O, but because both spin manifolds can produce both products, and the uncertainty in the yield encompasses the predicted methanol branching fractions on both surfaces, it is difficult to draw strong conclusions about the role of intersystem crossing in the reaction. However, the experiments considerably improve the uncertainty bounds on the yield, with the MPIMS-determined yields in remarkable agreement with the high-level calculations. Characterisation of the methanol signal in the MPIMS experiment via photoionization energy spectroscopy through comparison with the known literature photoionization energy spectra (Supplementary Figs. 4, 5) and cross-sections shows that the methanol branching fraction can be robustly determined. Our calculations (Supplementary Note 3) demonstrate the potential contribution of the trioxide to the methanol signal in the PTR-TOFMS detection, in addition to possible heterogenous conversion pathways. This is consistent with our detection of the trioxide at higher pressures in the MPIMS experiment. The MPIMS value of 6–9% reflects the direct reaction product branching fraction.

Inclusion of this reaction in a global atmospheric chemistry and transport model could not improve the methanol discrepancy between model and observations; the direct methanol branching fraction results in a factor of 1.5 underprediction of methanol in
Methods

Experiments. Measurements were performed at 298 K and 30 Torr using the Sandia Multiplexed Photoionization Mass Spectrometer (MPIMS) instrument coupled to the tuneable-VUV-output of the Chemical Dynamics Beamline (9.0.2) at the Advanced Light Source, Lawrence Berkeley National Laboratory. Reagent (CH₃I or ¹³CH₃I, H₂O₂, O₂) and bath gases (He) were flowed into a halocarbon wax-coated quartz reactor via a set of calibrated mass flow controllers. H₂O₂ was produced by heating urea hydrogen peroxide and was entrained into the He flow via a pressure- and temperature-controlled bubbler. At the high concentration of O₂ utilised in the experiments (2.6 × 10^{17} cm⁻²) a significant O₂ peak was observed m/z = 32, ionised by the small amount of transmitted higher undulator harmonics. Because the masses of ^16O₂ (31.98984 amu) and ^12CH₃OH (32.02622 amu) could not be completely resolved, experiments were performed using ¹³CH₃OO, such that the resultant methanol signal was well separated in mass from O₂.O H. Measurements were performed at 740 Torr were carried out in a quartz—Chamber experiments were performed in a 300 L Te—suspended in a closed box where photolysis of O₃ in the presence of water vapour (2.5–3.8 × 10^{16} cm⁻²) was carried out using 1–8 Hg lamps. Methane (5% in N₂, Air remote environments. This work highlights the necessity for further characterisation of potential atmospheric methanol sources, including understanding the tropospheric fate of the trioxide (5). Moreover, Khan et al. determined that up to 17% of peroxy radicals may be complexed to a single water molecule under atmospheric conditions, and previous work has demonstrated an impact of water complexation on reaction rate coefficients and product branching fractions. The near-atmospheric pressure measurements here were carried out at low relative humidity (RH); further investigations as a function of RH may help to determine whether a water effect on reaction 2, or perhaps unexplored functionalized peroxy radical cross-reactions, may be part of the missing source of atmospheric methanol.

Fig. 4 The impact of the title reaction on key atmospheric species with a 7% methanol yield. Annual surface percentage changes in a OH b HO₂ c O₃ d CO e HCHO f CH₂O g CH₂OOH h ROOH (excluding CH₃OOH), and i CH₃OH upon inclusion of the OH + CH₃OOH reaction with assumed branching fractions \( \phi_2 = 0.93, \phi_3 = 0.00, \phi_4 = 0.07, \phi_5 = 0.00 \)
**Fig. 5** The impact of the title reaction with different methanol yields on global methanol. Annual surface percentage changes in CH$_3$OH on inclusion of the OH + CH$_3$OO reaction compared with the base case model with the branching fractions for channel 4 of a 0.1 b 0.15 c 0.2 and d 1 and for channel 2 of a 0.9 b 0.85 c 0.8 and d 0, respectively.

**Fig. 6** Comparison of methanol field measurements with modelled outcomes as a function of altitude. Vertical profiles of measured and modelled CH$_3$OH over a tropical Pacific b midlatitude Atlantic and c Pacific. The data compilation of Müller et al.\textsuperscript{18} containing measured CH$_3$OH are used for the model-measurement comparison. Violet square symbols represent mean CH$_3$OH produced for the base case (without the OH + CH$_3$OO reaction). Blue triangle, green diamond, yellow star, orange plus and red circle symbols represent mean CH$_3$OH produced at the branching fractions of the channel of 0.07, 0.1, 0.15, 0.17 and 0.2, respectively. Black triangles represent the measurement CH$_3$OH data and the black error bars represent measurement variability (standard deviation).
Liquide) was introduced in the reactor using ml syringes to get initial concentrations between 1.8 × 10^14 and 3.7 × 10^14 cm^-3. The CH4 relative concentrations were determined both by infrared spectroscopy at around 1800 cm^-1 and by high-resolution proton-transfer reaction time-of-flight mass spectrometry (HR-PT-TOFMS Ionicon 8000). Although the CH4 proton affinity is lower than the proton affinity of a small signal scaling with the CH4 concentration was detected by the PTR-TOFMS instrument due to the high concentrations used in these experiments. Ozone was produced by a commercial O3 generator (C-Lasky, AirTree Europe GmbH) and initial concentrations of (2.0–8.4) × 10^12 cm^-3 were obtained. The O3 time-dependent concentrations were measured using a UV absorption analyser (Environnement SA 42 M) while methanol and formamide were measured by PTR-TOFMS. Absolute methanol concentrations were determined after daily calibrations of the PTR-TOFMS transmission curve using a Gas Calibration Unit (GCU, IONICON) and a gas standard composed of methanol, acetalddehyde, acetone, benzoene, o-xylene and 1,2-dichlorobenzene (IONICON, 10 uncertainty for each species of 5–6%). Formaldehyde measurements were also calibrated by adsorption on 2,4-Dinitro Phenyl Hydrazine cartridges and analysis through High-Pressure Liquid Chromatography (HPLC-UV) for some of the experiments. The agreement between PTR-TOFMS and HPLC was within 20%. Methanol and formaldehyde wall losses were also negligible (<1% h^-1).

Model. The STOCHEM-CRI model has been described in previous papers3,5,37,38 and pertinent details are given herein.

STOCHEM is a global 3-dimensional chemistry transport model that adopts a Lagrangian approach splitting the troposphere into 50,000 constant mass air parcels. As it is a Lagrangian model, the transport and chemistry can be conducted with meteorology from 1998 for a period of 24 months with the mean values calculated using the MATCH global model45. The scavenging and physical removal processes (dry and wet deposition) used in STOCHEM were adapted from the annual inventory for the year 199848. More details about the emissions data can be archived within the code itself. Each air parcel contains the complete 229 species in the Master Chemical Models (MCM version 3.1)42. More details of the CRI v2-R5 mechanism used in STOCHEM is the common representative intermediates of photolysis reactions were calculated by integrating (overall wavelengths) the absorption cross sections for methanol, ethanol, methyl bromide, and 1,2-dichlorobenzene (IONICON, 1

Data availability

The datasets generated in the current study are available from the corresponding authors on reasonable request.

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R.L.C., I.S., C.F., A.T., S.D., C.J.P., D.E.S. and C.A.T. planned the experiments. R.L.C., M.A.H.K., J.Z., D.E.S. and C.A.T. carried out the modelling work. Data analysis was undertaken by R.L.C., I.S., C.F., A.T., S.D., C.J.P., D.E.S. and C.A.T. Experimental work was performed by R.L.C., I.S., C.F., A.T., S.D., C.J.P., D.E.S. and C.A.T. Experimental work was performed by R.L.C., I.S., C.F., A.T., S.D., C.J.P., D.E.S. and C.A.T. Experimental work was performed by R.L.C., I.S., C.F., A.T., S.D., C.J.P., D.E.S. and C.A.T. Experimental work was performed by R.L.C., I.S., C.F., A.T., S.D., C.J.P., D.E.S. and C.A.T. Experimental work was performed by R.L.C., I.S., C.F., A.T., S.D., C.J.P., D.E.S. and C.A.T. Experimental work was performed by R.L.C., I.S., C.F., A.T., S.D., C.J.P., D.E.S. and C.A.T.

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