The reaction of methyl peroxy and hydroxyl radicals as a major source of atmospheric methanol

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Methyl peroxy, a key radical in tropospheric chemistry, was recently shown to react with the hydroxyl radical at an unexpectedly high rate. Here, the molecular reaction mechanisms are elucidated using high-level quantum chemical methodologies and statistical rate theory. Formation of activated methylhydrotrioxide, followed by dissociation into methoxy and hydroperoxy radicals, is found to be the main reaction pathway, whereas methylhydrotrioxide stabilization and methanol formation (from activated and stabilized methylhydrotrioxide) are viable minor channels. Criegee intermediate formation is found to be negligible. Given the theoretical uncertainties, useful constraints on the yields are provided by atmospheric methanol measurements. Using a global chemistry-transport model, we show that the only explanation for the high observed methanol abundances over remote oceans is the title reaction with an overall methanol yield of ~30%, consistent with the theoretical estimates given their uncertainties. This makes the title reaction a major methanol source (115 Tg per year), comparable to global terrestrial emissions.
Methyl peroxy radical (CH$_3$O$_2$) is the most important organic peroxy radical in the atmosphere, with a global production (~50 Tmol or 2,500 Tg per year) primarily due to the oxidation of ubiquitous methane by hydroxyl (OH) radicals. Its reaction with nitric oxide (NO) accounts for ~25% of the global production of tropospheric ozone\(^{2,3}\), second in importance only to HO$_2$ + NO. Under pristine conditions, CH$_3$O$_2$ reacts chiefly with hydroperoxy radicals HO$_2$ to form methyl hydroperoxide CH$_3$OOH, depleting odd hydrogen radicals (HOx = OH + HO$_2$) directly and through the further reaction of CH$_3$OOH with OH. The reaction of CH$_3$O$_2$ with organic peroxy radicals (RO$_2$) is only a minor sink\(^4\), but it is also the only well-documented photochemical source of atmospheric methanol, amounting to 18–38 Tg per year globally according to model estimates\(^5\). Note that a much larger total photochemical source (50–100 Tg per year) was invoked by Jacob et al.\(^6\) to rationalize serious model underestimates of methanol observations during an aircraft campaign over the Pacific\(^6\).

Although the possibility of a reaction of CH$_3$O$_2$ with OH was previously considered\(^7,8\), it is only recently that a direct, absolute determination of its rate has been reported. Coupling Laser Induced Fluorescence and cw-Cavity Ring-Down Spectroscopy to laser photolysis, Bossolasco et al.\(^9\) measured a rate of (2.8 ± 1.4) × 10$^{-10}$ cm$^3$ molecule$^{-1}$ s$^{-1}$. This unexpectedly high value makes this reaction a major sink of CH$_3$O$_2$ in pristine conditions. Using campaign data in Cape Verde, Fittschen et al.\(^10\) estimated that it accounts for ~25% of the overall CH$_3$O$_2$ sink at that remote site, rivalling the reaction with HO$_2$. Its impact on atmospheric chemistry is however critically dependent on the nature and yields of the products. Three exothermic overall reaction channels were envisaged\(^6\):

\[
\begin{align*}
\text{OH} + \text{CH}_3\text{O}_2 & \rightarrow \text{CH}_3\text{O}_2 + \text{H}_2\text{O} & (1) \\
\text{OH} + \text{CH}_3\text{O}_2 & \rightarrow \text{CH}_3\text{O} + \text{HO}_2 & (2) \\
\text{OH} + \text{CH}_3\text{O}_2 & \rightarrow \text{CH}_3\text{OH} + \text{O}_2 & (3)
\end{align*}
\]

with CH$_3$O$_2$ the singlet Criegee intermediate, H$_2$C=O(1$^+$)+O(1$^-$). The Criegee channel (1) has been invoked as the possible source of a missing oxidant of SO$_2$ inferred from observations at a coastal site\(^11\). A large Criegee yield would also lead to a very large source of formic acid through reaction of stabilized CH$_3$O$_2$ with water\(^12\). The reaction was therefore speculated\(^8,13\) to explain part of the missing source of HCOOH required to sustain the high HCOOH levels observed in the atmosphere\(^14,15\), although it was found to degrade model/data correlation for measurement campaigns over the U.S.\(^13\).

The methoxy channel (2) leads ultimately to two HO$_2$ radicals and formaldehyde, which is the end product of both CH$_3$O$_2$ + NO and (through CH$_3$OOH) CH$_3$O$_2$ + HO$_2$. The methanol channel (2) was noted to be a potentially very significant source of methanol\(^8,13\), but no quantitative assessment has been made to this date.

A recent quantum chemical study of CH$_3$O$_2$ + OH by Bian et al.\(^16\) could identify only one thermally accessible pathway commensurate with the high measured rate constant: combination of the reactants into an activated methylhydrotrioxide CH$_3$OOOH (TRIOX), followed by direct dissociation into CH$_3$O and HO$_2$, which are about 4 kcal mol$^{-1}$ more stable than the reactant radicals. Another recent theoretical study by Nguyen et al.\(^17\) briefly addressed the reaction, concluding that the dominant pathway in atmospheric conditions is collisional stabilization of CH$_3$OOOH, whereas production of Criegee is negligible.

In view of the likely major importance of the title reaction for key oxygenated organic compounds and its potentially large impact on HOx radicals in the remote troposphere, this work proposes to: (i) elucidate the molecular mechanisms of the reaction by constructing detailed potential energy surfaces, using suitable high-level density functional theory (DFT) and ab initio methodologies for the singlet and triplet (biradical) intermediates; (ii) identify the kinetically viable reaction channels and distinguish between the major and minor product routes using appropriate statistical rate theories; (iii) use a global chemistry-transport model, the Intermediate Model for the Annual and Global Evolution of Species (IMAGES, see the ‘Methods section’), to assess the impact of the reaction and constrain the yields through comparisons with atmospheric measurements. For those readers most interested in the implications for atmospheric chemistry, the results relating to goals (i) and (ii) are succinctly summed up before the section on atmospheric modelling, and we invite such readers to move directly to this summary.

**Results**

**Potential energy surface and reaction kinetics.** We characterized all three exothermic overall reaction channels (reactions (1), (2), (3)) and all other relevant pathways of the title reaction using quantum chemical methods. Structures and vibrational frequencies were computed with DFT, at the M06-2X-D3/6-311++G(3df,3pd) level of theory (Supplementary Fig. 1, Supplementary Fig. 2, and Supplementary Table 1). More accurate energies were computed using coupled-cluster theory, with explicit (‘F12’) treatment of electron–electron distances, as shown in Fig. 1. The DFT and coupled-cluster calculated properties of various complexes and transition states are summarized in Table 1.

The reaction of CH$_3$OO with OH starts by the barrier-less formation of singlet reactant complex $^1$RC and triplet reactant complex $^3$RC, in which OH donates a hydrogen bond to CH$_3$OO, and in which the singlet and triplet states are near degenerate. Hydrogen abstraction starting from $^1$RC and $^3$RC to form the Criegee intermediate $^1$CH$_3$OO and the triplet biradical $^3$CH$_3$OO via TS$_2$ and TS$_3$, respectively, involve significant barriers. In absence of intersystem crossing (ISC) $^3$RC $\rightarrow$ $^1$RC, the reaction CH$_3$O$_2$ + OH $\leftrightarrow$ $^3$RC will be quasi-equilibrated such that the bimolecular rate constant for the overall triplet channel CH$_3$O$_2$ + OH $\rightarrow$ $^3$CH$_3$OO + H$_2$O can be found from transition state theory (TST)\(^18-20\), yielding $^3$R$_{b,3}(298\text{ K}) = 2.6 \times 10^{-15}$ cm$^3$ molecule$^{-1}$ s$^{-1}$. This channel is therefore entirely negligible, as are the other triplet entrance routes described by Bian et al.\(^16\), all proceeding through transition states that lie even much higher. Instead, rapid ISC of $^3$RC to the nearly-degenerate $^1$RC could channel much of the triplet entrance flux also towards the singlet surface and hence to TRIOX (see below), rationalizing the high measured overall rate constant\(^5\) of 2.8 × 10$^{-10}$ cm$^3$ molecule$^{-1}$ s$^{-1}$.

The favoured reaction channel of the chemically activated $^1$RC is the formation of the stable methylhydrotrioxide TRIOX over the very low-energy TS$_1$. Direct dissociation of TRIOX into CH$_3$O and HO$_2$ is not a minimum energy pathway; instead, the energetically favoured decomposition route passes through the singlet product complex $^1$PC over TS$_4$, which involves concerted CH$_3$O–OOH bond-breaking and formation of a CH$_3$O–HO$_2$ hydrogen bond. The relative energy and vibrational properties of saddle-point TS$_4$ play an important role in determining selectivity, but this point is also very difficult to characterize accurately. As explained below, the best results are obtained by using a structure optimized with the M06-D3 DFT method, rather than M06-2X-D3 as used for the other stationary points. Like the reactant complex, the hydrogen-bonded PC has near-degenerate singlet and triplet states. From $^1$PC, CH$_3$O + HO$_2$ can be formed through TS$_5$, or CH$_3$OH + O$_2$ can be obtained through TS$_7$. Equally, $^3$PC can convert to triplet...
product complex $^3$PC, and $^3$PC can form CH$_3$OH + $^3$O$_2$ through the very low TS6.

Transition states TS2, TS3, TS5, TS6 and TS7 corresponding to the abstraction or transfer of a hydrogen atom are straightforward and their identity has been carefully confirmed using intrinsic reaction coordinate (IRC) calculations. The coupled-cluster relative energies agree well with those from DFT, supporting the use of the M06-2X-D3 functional for geometry optimization. However, TS1 and TS4 are more problematic and need further discussion, in particular as these crucial transition states (TSs) largely determine the dominant reactant pathways. Both TSs can be considered to correspond to breaking of one of the O–O bonds in TRIOX. However, this step does not proceed with monotonously increasing energy towards the fragments, due to the existence of the hydrogen-bonded RC and PC. As the relative orientation of the fragments in the complexes differs from that in TRIOX, the TSs have combined O–O bond breaking and fragment reorientation character. Also, TRIOX has a closed-shell singlet electronic structure, with the transition to the open-shell radical pair nature of PC or RC occurring in the region near the TSs. For open-shell singlets with completely uncoupled electrons, singlet and triplet states are near-degenerate (as in RC and PC). Unrestricted DFT calculations and coupled-cluster calculations based on unrestricted Hartree-Fock reference wavefunctions are reasonably accurate in this case. However, for partially uncoupled electrons, the triplet is significantly higher in energy, and unrestricted approaches are less accurate, introducing artefacts in the shape of the energy curve. For TS1, we are able to locate two saddle points, TS1 and TS1', with the M06-2X-D3 functional. The first one corresponds mostly to reorientation of the OH fragment, while TS1' has essentially only O–O bond stretching character. Large-active-space CASSCF (complete active space self-consistent field) and CASPT2 (complete active space perturbation theory 2) calculations (Supplementary Fig. 3 and Supplementary Note 1), which can treat systems with partially uncoupled electrons in a balanced way, strongly suggest TS1' to be purely an artefact based on inaccurate description of the developing low-spin open-shell electronic structure, whereas the TS1 is more reliable.

For TS4, only one TS structure, TS4', is obtained with M06-2X-D3, but CASSCF and CASPT2 calculations show it is an artefact, similar to TS1'. In contrast, the M06-D3 functional yields a TS structure, denoted TS4, which is closer to the correct TS according to CASSCF and CASPT2. The difference in structure is quite large: the M06-2X-D3 TS4' structure is very ‘early’ (O–O distance of 1.967 Å) whereas the M06-D3 TS4 has an O–O distance of 2.447 Å. Accordingly, we have used the TS4 structure in this study. For the other stationary points, the CASSD(T)-F12 (coupled cluster—single, double and triple excitation theory) total energies at the M06-D3 and M06-2X-D3 structures differ by <0.2 kcal mol$^{-1}$, and the vibrational frequencies are very similar also.

The chemically activated singlet reactant complex $^1$RC, with average vibrational energy $\langle E_v \rangle = 4.8$ kcal mol$^{-1}$, including an average 2.1 kcal mol$^{-1}$ thermal energy at 298 K inherited from
the reactants (see the ‘Methods section’), reacts nearly barrier-free (TS1) to form the closed-shell CH$_3$OOOH molecule, TRIOX, much faster than forming Criegee CH$_3$O$_2$ and H$_2$O over a barrier of 3.7 kcal mol$^{-1}$ (TS2). The RRKM-based (Rice, Ramsperger, Kassel, Marcus) unimolecular rate coefficients averaged over the (narrow) distribution function of formation $F(E_{th,v})$ (see the ‘Methods section’) are $<k>_1 = 1.8 \times 10^{13}$ s$^{-1}$ and $<k>_2 = 3.4 \times 10^{10}$ s$^{-1}$, respectively. The $k$-subscripts refer to the TS numbering in Fig. 1. All $F(E_{th,v})$-averaged rate coefficients of the activated reaction steps given in this subsection are for 298 K and 1,013 hPa (air). They are listed also in Table 2, together with the values for 285 K and 750 hPa, as well as these for 256 K and 400 hPa (see next subsection). Since the various chemically activated reactions.

TRIOX, with average chemical activation energy $<E_a>$ of 31.1 kcal mol$^{-1}$ (at 298 K) converts rapidly to the product complex PC over the low-lying and very loose TS4, characterized above, far outrunning the other isomerization/decomposition reactions through high-lying transition states$^{16}$. The rate coefficient integrated over the formation distribution function $F(E_{th,v})$ is evaluated at $<k>_1 = 2.4 \times 10^{10}$ s$^{-1}$, implying a TRIOX lifetime of $\sim 40$ ps during which it should lose $\sim 0.45$ kcal mol$^{-1}$ by collisions at 298 K and 1,013 hPa (see below), shifting down also the energy distribution $F(E_{th,v})$ for PC. The CH$_3$O•HOO complex PC has a decisive role in our system; the $\sim 7$ kcal mol$^{-1}$ strong CH$_3$O–HOO hydrogen bond explains why the minimum energy pathway of CH$_3$OOOH to CH$_3$O + HO$_2$ passes through it. The fastest reaction of PC, with $<E_a>$ (PC) $\approx 12.4$ kcal mol$^{-1}$, is dissociation into these radicals by breaking the H-bond without exit barrier. The $F(E_{th,v})$-averaged $<k_{diss}>$ was estimated by variational RRKM$^{11,12}$. The energy, zero-point vibrational energy (ZPVE) and integrated density of states $G^{var}(E_v-E^{var})$ were computed for a series of structures with increasing H-bond length, using the unprojected vibrational frequencies, as listed in Supplementary Table 2; the use of projected frequencies$^{23-25}$ for the sum of states would have resulted in $\sim 12$% higher $<k_{diss}>$ and $<k_{diss}^{3}>$, with a minor effect on the overall product yields (see Supplementary Note 3). The variational bottleneck that minimizes $G^{var}(E_v-E^{var})$, shown in Fig. 2, was found for an H-bond length of 3.2 Å, and relative energy 1.7 kcal mol$^{-1}$ below the separated CH$_3$O + HO$_2$, giving $<k_{diss}> \approx 2.4 \times 10^{12}$ s$^{-1}$.

The decomposition of PC into CH$_3$O + HO$_2$ over the fairly high TS5, with RRKM-calculated rate of only $<k>_5 = 9.7 \times 10^{7}$ s$^{-1}$ is negligibly slow, whereas decomposition into CH$_3$O + O$_2$ over TS7, at averaged rate $<k>_7 = 1.2 \times 10^{11}$ s$^{-1}$, is a channel of atmospheric relevance. Importantly, conversion of the initially formed PC to PC will affect the relative yields of the different products. Spin–orbit coupling between the lowest singlet and triplet states in PC is very small, but the spin–orbit coupling between the lowest singlet state and the second-lowest triplet state (or between the second-lowest singlet and the lowest triplet) is much larger, as there is now an orbital angular momentum difference, and we calculate a root-mean-square coupling matrix element of 58 cm$^{-1}$ in both cases. Simply assuming Rabi cycling between the two states, a ‘rate constant’ for singlet-triplet conversion of $1.7 \times 10^{12}$ s$^{-1}$ is estimated. Using a more rigorous statistical rate theory for reactions with spin-state change$^{26,27}$ (see Supplementary Note 2), we obtain a remarkably similar estimate of $<k^{isc}> = 3.5 \times 10^{12}$ s$^{-1}$, while the reverse $<k_{isc}^{TS}> = 1.9 \times 10^{12}$ s$^{-1}$. The reverse reaction PC $\rightarrow$ TRIOX occurs with an average rate $<k_{TS}>$ for an average $<k_{TS}>$ of $3.1 \times 10^{11}$ s$^{-1}$, which is $\sim 3$% of the total PC removal rate, such that the net TRIOX $\rightarrow$ PC conversion rate $k^{1}_{TS}(E_v) = 0.97 \times k_{TS}(E_v)$.

PC decomposes into CH$_3$O and ground state O$_2$ over a very low barrier (TS6), with RRKM-calculated average $<k_{diss}^{3}>$ of 4.1 $\times 10^{11}$ s$^{-1}$, faster than the singlet PC reaction to CH$_3$OH,

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure2.png}
\caption{Dissociation of product complex and the variational transition state. Bond lengths are in angstrom. Angles are in degrees.}
\end{figure}

### Table 2 | RRKM-calculated rate coefficients $<k(E_v)>$ averaged over the thermal energy distribution of formation $F(E_{th,v})$ for the various chemically activated reactions.

| Reaction step | Notation | $<k>$ (298 K) (1,013 hPa) | $<k>$ (285 K) (750 hPa) | $<k>$ (256 K) (400 hPa) |
|---------------|----------|--------------------------|--------------------------|--------------------------|
| $[^{1}RC \rightarrow \text{TRIOX}]$ | $<k>_1$ | $1.82 \times 10^{13}$ | $1.81 \times 10^{13}$ | $1.76 \times 10^{13}$ |
| $[^{1}RC \rightarrow \text{CH}_3\text{O}_2 + \text{H}_2\text{O}]$ | $<k>_2$ | $3.36 \times 10^{10}$ | $2.56 \times 10^{10}$ | $1.20 \times 10^{10}$ |
| $\text{TRIOX} \rightarrow \text{PC}$ | $<k>_4$ | $2.38 \times 10^{10}$ | $2.25 \times 10^{10}$ | $1.90 \times 10^{10}$ |
| $\text{PC} \rightarrow \text{H}_2\text{O} + \text{O}_2$ | $<k>_{diss}^{3}$ | $1.29 \times 10^{11}$ | $1.29 \times 10^{11}$ | $1.23 \times 10^{11}$ |
| $\text{PC} \rightarrow \text{CH}_3\text{O} + \text{HO}_2$ | $<k>_{diss}^{3}$ | $2.43 \times 10^{12}$ | $2.41 \times 10^{12}$ | $2.32 \times 10^{12}$ |
| $\text{PC} \rightarrow \text{PC} + \text{PC}$ | $<k>_{diss}^{3}$ | $3.50 \times 10^{12}$ | $3.50 \times 10^{12}$ | $3.44 \times 10^{12}$ |
| $\text{PC} \rightarrow \text{PC} + \text{PC}$ | $<k>_{diss}^{3}$ | $1.87 \times 10^{12}$ | $1.87 \times 10^{12}$ | $1.84 \times 10^{12}$ |
| $\text{PC} \rightarrow \text{CH}_3\text{O} + \text{HO}_2$ | $<k>_{diss}^{3}$ | $9.67 \times 10^{9}$ | $9.67 \times 10^{9}$ | $9.29 \times 10^{9}$ |
| $\text{PC} \rightarrow \text{CH}_3\text{O} + \text{HO}_2$ | $<k>_{diss}^{3}$ | $3.37 \times 10^{12}$ | $3.36 \times 10^{12}$ | $3.23 \times 10^{12}$ |
| $\text{PC} \rightarrow \text{CH}_3\text{OH} + \text{O}_2$ | $<k>_{diss}^{3}$ | $4.14 \times 10^{11}$ | $4.14 \times 10^{11}$ | $4.14 \times 10^{11}$ |
| $\text{PC} \rightarrow \text{CH}_3\text{OH} + \text{O}_2$ | $<k>$ | $1.20 \times 10^{11}$ | $1.20 \times 10^{11}$ | $1.20 \times 10^{11}$ |

For formation of $[^{1}RC \rightarrow \text{TRIOX}]$, $F(E_{th,v})$ is the initial thermal distribution; for $[\text{PC} \rightarrow \text{PC}]$ and $[\text{PC} \rightarrow \text{PC}]$, $F(E_{th,v})$ is shifted down by collisions, by 0.45, 0.35 and 0.25 kcal mol$^{-1}$ at 298, 285 and 256 K, respectively (see text).

$<k>$-value obtained using variational RRKM.

Rate coefficient of triplet $[\text{PC} \rightarrow \text{PC}]$ reaction preceded by superscript 3 for clarity.
above. It must compete with the reverse ISC, above and also with the fast dissociation of $^3$PC into CH$_3$O + HO$_2$ at variational-RKRK rate $<$$^3$$k_{\text{diss}}$$>$ ≈ 3.4 × 10$^{12}$ s$^{-1}$ (see data in Supplementary Table 3), but still results in twice more CH$_3$OH $+$ O$_2$ production than the CH$_3$OH $+$ O$_2$ afforded by $^1$PC, above. Accounting for the rates of all reactions of $^1$PC and $^3$PC, the two latter routes together are found to result in a CH$_3$OH yield through activated TRIOX of 7.8% at 298 K and 1,013 hPa. Given the possible error of ~1.5 kcal mol$^{-1}$ on the energies of the transition states to CH$_3$OH relative to the (variational) transition states of the PC dissociations, and taking into account also a likely error of a factor of ~2 on the ratio of $k_{\text{ISC}}/k_{\text{diss}}$, we estimate an uncertainty margin on the CH$_3$OH yield of a factor of ~3.5. Note that about 45% of the products of activated TRIOX arise via ISC of $^1$PC to $^3$PC. Of major importance is that TRIOX does not decompose directly but via the complex $^3$PC, which enables production of CH$_3$OH, while direct methanol formation from CH$_3$OOOH would face a quasi-unsurmountable barrier.$^{16}$

A (minor) fraction of the activated TRIOX will suffer energy loss by successive collisions with air molecules to yield thermalized CH$_3$OOOH, of which the subsequent fates are discussed in Supplementary Note 4. Using the bi-exponential energy transfer model of Troe$^{28}$ with an assumed average energy transferred per collision $<$$\Delta$$E$$>$,$^\text{all}$ of ~0.9 kcal mol$^{-1}$—fairly high because TRIOX has several low-frequency vibration modes—and taking into account the distribution function $F(E_{\text{th,v}})$ of the activated TRIOX, the fraction of stabilization at a collision frequency of 1.2 × 10$^{13}$ s$^{-1}$ at 298 K and 1,013 hPa was evaluated (see the 'Methods section') to be $f_{\text{stab}}$≈ 10.7%. However, this result is quite uncertain, first of all because it is very sensitive to the assumed value of $<$$\Delta$$E$$>_{\text{all}}$: doubling it increases $f_{\text{stab}}$ nearly threefold while halving it reduces $f_{\text{stab}}$ to < 2%. Moreover, the calculated $f_{\text{stab}}$ depends also strongly on $k_4(E_f)$, which itself bears a possible error of a factor ~1.5–2. We therefore estimate a stabilized CH$_3$OOOH yield at 298 K and 1 atm in the range 0–35%. The much higher $f_{\text{stab}}$ of ~90% predicted by Nguyen et al.$^{17}$ can be ascribed to their TS for TRIOX→$^1$PC conversion being our artefactual TS4, which on account of its far higher rigidity than TS4 leads to a much lower calculated rate of TRIOX→$^1$PC and hence much more TRIOX stabilization.

**Reaction products and estimated yields in the troposphere.** The theoretical investigation above predicts that the dominant product route of the title reaction is channel (2) yielding the radicals CH$_3$O + HO$_2$, whereas the suggested channel (1)$^{8,9}$ producing the Criegee Intermediate CH$_3$O$_2$ is found to be entirely negligible. On the other hand, we find that the title reaction yields a sizable fraction of collisionally thermalized (but chemically labile) CH$_3$OOOH, of order of 10% at 1 atm and 298 K, while we also uncovered two parallel pathways leading directly to CH$_3$OH + O$_2$ with overall yield around 7% in the same conditions. No evidence could be found for any other significant product routes. It must be stressed that the yield estimates of CH$_3$OOOH and CH$_3$OH given above and listed in Table 3 are subject to large uncertainty factors of ~3.5 for each, as detailed in the previous subsection.

As detailed in the next subsection, the title reaction is most important above the tropical oceans, where NO levels are low but OH concentrations moderate to high. The rate of the reaction as a function of decreasing pressure (or of increasing altitude) and as a function of latitude is depicted in Supplementary Fig. 4. Near the Equator, accounting for the temperature profile, ~50% of the
reaction occurs below 750 hPa (altitude ~ 2.4 km) where the average temperature is 285 K, and nearly ~95% below 400 hPa (altitude ~ 7.5 km) where temperature is 256 K. Given that the CH₃OOH stabilization fraction should show a considerable pressure and temperature dependence, and a minor temperature dependence is also expected for other pathways (see the ‘Methods section’) we have evaluated the CH₃OOH and CH₃OH yields also for the ‘median’ conditions 750 hPa and 285 K, and for the ‘limit’ conditions 400 hPa and 256 K, above. The results, together with those for 1,013 hPa and 298 K, are listed in Table 3. The pronounced pressure- and temperature dependences of the CH₃O₂ stabilization fraction can be expressed within a few per cent by the power function \( f_{stab}(P,T) = 0.107 \times (P/1,013 \text{ hPa})^{2.0} \times (298 \text{ K}/T)^{0.0}. \)

**Modelled global impact.** Adopting the measured rate⁶ of CH₃O₂ + OH, the reaction accounts for 20% of the global CH₃OH sink according to IMAGES simulations. The global flux through that reaction is considerable: ~11 Tmoles per year, comparable to, for example, the global source of isoprene 29. Although it is only a minor sink (~10%) of CH₃O₂ at high latitudes and over polluted continental regions (Fig. 3) where the reaction with NO is by far the largest sink (Supplementary Fig. 5), the reaction with OH represents 20–30% of the sink over tropical oceans and deserts, where CH₃O₂ + HO₂ is however still dominant (30–50% of total sink).

Table 4 summarizes the model simulations. The three best theoretical estimates are used in run B, while runs C and D adopt yields approaching respectively the high end and low end of the estimated uncertainty range of both the direct CH₃OH yield and the TRIOX stabilization fraction. Relative to a simulation neglecting the title reaction, the HO₂ radical abundances are increased by 10–20% over tropical oceans (Supplementary Fig. 6). Unsurprisingly, the impact is highest when the HO₂ yield is highest (run D). The changes are negligible or even negative in high-NOₓ areas.

The changes in OH are of opposite sign to those of HO₂, reaching up to ~7% over remote oceans. Loss of OH due to reaction with CH₃O₂ and the products CH₃OOH and CH₃OH is partially offset by OH recycled from enhanced HO₂. The globally averaged OH concentration decreases by 1.5–3.2% depending on the simulation, increasing the methane lifetime by up to 0.3 years in run C. The largest OH changes are calculated in run C, due to its lower HO₂ yield and higher OH loss through reaction with CH₃OOOH and CH₃OH. Surface ozone is decreased due to the CH₃O₂ + OH reaction, by up to 6% over remote oceans, and by 1–2% (<1 ppbv) over Europe, North America and East Asia in July (Supplementary Fig. 7). Hydrogen peroxide (H₂O₂) is strongly impacted, owing to the quadratic dependence of its production on HO₂ levels. Its concentrations increase by up to 30% in run C (Fig. 4) and ~50% in runs B and D.

Methyl peroxy radical abundances are reduced by up to 40% over tropical oceans (Fig. 4), irrespective of the yield assumption. This strong drop in concentration reflects increased loss through reaction with OH and HO₂, and slightly decreased production from CH₄ + OH. The decreases in CH₃OOH are also substantial (up to ~30%). Formaldehyde is almost unaffected, being an end product to all CH₃O₂ sink pathways. Methanol, however, shows drastic differences among the simulations: whereas its concentrations increase or decrease by ~20% at most in runs B and D, the global methanol burden is increased by 60% in run C, with concentration increases reaching 30–100% over remote oceans (Fig. 4). Even over continents, methanol increases by 10–20% over most areas and by 80–200% over desert regions with very low methanol emissions. Methanol formation from CH₃O₂ + OH is largely due to the direct pathway to CH₃OH + O₂ (56%), but indirect formation through stabilized TRIOX is significant (44%). Reaction on aerosols is calculated to be the largest TRIOX sink, globally, followed by reaction with OH and reaction with (H₂O)₂ (Supplementary Fig. 8, Supplementary Note 4). The calculated average yield of methanol from stabilized TRIOX is 65%.

**Model evaluation for peroxides and formaldehyde.** We limit our evaluation to stable compounds over oceans, where strongest impacts are expected. Both the modelled vertical profile and latitudinal profile of H₂O₂ agree generally fairly well with the observations from aircraft and ship campaigns (Supplementary Fig. 9, Supplementary Fig. 10, and Supplementary Fig. 11), indicating that its sources and sinks are reasonably well described by the model. As seen in Supplementary Table 4, the average model bias across all campaigns is improved when including the title reaction, from −14% in run A to +3% and −2% in runs B and C, respectively. Although this improvement could be fortuitous, given the known uncertainties in HOₓ modelling³⁰, the title reaction clearly does not lead to noticeable inconsistencies with the data. As expected, the reaction has negligible impact on modelled CH₂O (Supplementary Fig. 12) which agrees very well with aircraft data over oceans.

For CH₃OOH, the title reaction leads to model under-estimations (> ~25%) of airborne measurements, but it improves significantly the model agreement with ship measurements (Supplementary Fig. 11, Supplementary Fig. 13, and Supplementary Table 5). The contradiction between the conclusions from either ship or aircraft data is difficult to explain given the wide geographical area covered by both platforms. As in a previous modelling study¹³, the largest biases are

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**Table 4 | Overview of model simulations with assumed product yields.**

| Run | CH₃O₂ + OH | CH₃O | TRIOX | CH₃OH | CH₂OO |
|-----|------------|------|-------|-------|-------|
| A   | Ignored    | 0.86 | 0.07  | 0.07  | 0     |
| B   | Best estimate | 0.61 | 0.21  | 0.18  | 0     |
| C   | High methanol case* | 0.975 | 0     | 0.025 | 0     |
| D   | Low methanol case* | 0.6 | 0     | 0     | 0.4  |
| E   | High Criegee case†  | 0.61 | 0.21  | 0.18  | 0     |
| A_NO | As A, no ocean source‡ | -   | -     | -     | -     |
| C_NO | As C, no ocean source‡ | 0.61 | 0.21  | 0.18  | 0     |
| C_VR | As C, low k(CH₃OOH + OH)§ | 0.61 | 0.21  | 0.18  | 0     |

* Methanol yield from activated trioxide multiplied (divided) by 3 in run C (D) relative to best estimate. Stabilisation fraction multiplied by 3 in run C, taken equal to zero in run D.
† Not a theoretical prediction.
‡ Oceanic methanol emission omitted.
§ Use lower rate for reaction CH₃OOH + OH, within recommended uncertainty range.

Globally averaged molar yields of CH₂O, stabilized trioxide, CH₃OH and CH₂OO adopted in model runs. The yields are pressure- and temperature-dependent (see text).
found for INTEX-B (ref. 31). Since even the run ignoring the
title reaction largely underestimates the observations in several
campaigns, measurement issues and/or model uncertainties
likely cause the discrepancies. For example, the estimated
uncertainty in the rate constant of the \( \text{CH}_3\text{OOH}^+ + \text{OH} \)
reaction is a factor of 1.4 (ref. 32). Adopting a rate constant
measurement\(^{33}\) about 25% lower than the current Jet
Propulsion Laboratory recommendation\(^{32}\) used in the model
increases the \( \text{CH}_3\text{OOH} \) concentrations by 15–20% and goes
already a long way to compensating the deterioration of model
performance against aircraft campaigns (Supplementary Fig. 13
and Supplementary Table 5). Other relevant processes might be
also uncertain. More work is needed to address those issues.

**A large source of methanol.** In agreement with previous
studies\(^{3,4,5,34,35}\), our simulation omitting \( \text{CH}_3\text{O}_2 + \text{OH} \)
underestimates \( \text{CH}_3\text{OH} \) observations by a factor of \( \sim 2 \)
over the remote Pacific (Fig. 5). When including the reaction,
methanol production from \( \text{CH}_3\text{O}_2 + \text{RO}_2 \) is halved, from 33 to
15 Tg per year (Supplementary Table 6) due to its near-quadratic
dependence on \( \text{CH}_3\text{O}_2 \) levels. The \( \text{CH}_3\text{O}_2 + \text{OH} \) reaction would
therefore worsen the model underestimations unless methanol is
produced by the reaction with a sufficient yield. The model/data
mismatch is barely reduced in run B, with its low overall
methanol yield (\( \sim 12% \)), while it nearly vanishes in run C, with
an overall yield of 32%. Both the average concentration and
vertical profile shape are greatly improved in this case.

Similar conclusions hold for comparisons at the most remote
sites Mauna Loa and Cape Verde, which was shown to be under
mostly maritime and Saharan influences\(^{36}\) (Table 5, Supplementary

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**Figure 4** | Impact of \( \text{CH}_3\text{O}_2 + \text{OH} \) on key compounds abundances. Annually averaged modelled changes (in %) in near-surface concentrations of
(a) \( \text{H}_2\text{O}_2 \), (b) \( \text{CH}_3\text{OOH} \), (c) \( \text{CH}_3\text{OH} \) and (d) \( \text{CH}_3\text{O}_2 \) in the high methanol simulation (run C). Maps created using IDL version 8.2.3.

**Figure 5** | Measured and modelled methanol over the remote Tropical Pacific. Measurements from the Pacific Exploratory Mission in the tropical Pacific (PEM-Tropics-B)\(^{6}\). Solid (dotted) lines denote simulations including (excluding) the oceanic source of methanol. The number of measurements per altitude bin is indicated on the right. The error bars represent the s.d.’s of the measurements. The nominal precision of the measurements was 25% (ref. 65).
Theoretical results presented above leave little doubt that the Criegee pathway (1) is negligible in atmospheric conditions, that is, CH₂O₂ is not formed in any significant amount from CH₃O₂ + OH which therefore cannot be an important source of formalic acid. Actually, any sizable contribution of the reaction to HCOOH formation would lead to huge overestimations of its modelled concentrations over the Southern Pacific (Supplementary Fig. 18) where median concentrations of only 19 pptv were measured in the boundary layer during Fig. 15). The other campaigns listed in Table 5 were probably more impacted by continental emissions, which are likely overestimated in the model since they were derived by inverse modelling while neglecting the contribution of CH₂O₂ + OH. Nevertheless, including the reaction improves the model performance against airborne measurement at mid-latitudes (Supplementary Fig. 16). An overestimation of oceanic emissions likely contributes also to the strong model overestimation for the Atlantic Meridional Transect cruise AMT-22 (Supplementary Fig. 17), since flux measurements by eddy covariance during that campaign indicated no emission, only deposition with an average dry deposition velocity (0.68 cm s⁻¹) close to the corresponding model value (0.63 cm s⁻¹). Suppressing oceanic emissions in the model (run C_NO) leads to a much closer agreement with the latitudinal profile of AMT-22 data. That this setting leads however to large underestimations at other sites (Table 5) suggests that ocean/atmosphere exchanges are more variable than currently assumed.

**Discussion**

The theoretical results presented above leave little doubt that the Criegee pathway (1) is negligible in atmospheric conditions, that is, CH₂O₂ is not formed in any significant amount from CH₃O₂ + OH which therefore cannot be an important source of formalic acid. Actually, any sizable contribution of the reaction to HCOOH formation would lead to huge overestimations of its modelled concentrations over the Southern Pacific (Supplementary Fig. 18) where median concentrations of only 19 pptv were measured in the boundary layer during spring, almost an order of magnitude below modelled values assuming a 40% stabilized CH₂O₂ yield.

The theoretical calculations further inform us that the methoxy pathway (2) is expected to dominate, whereas both methanol formation (3) and stabilization of the trioxide are viable, but likely minor. Of fundamental interest is that significant direct methanol production can occur only because the activated CH₃OOO• complex decomposes indirectly through the CH₃O• + HO₂ complex. The share of each of the two minor channels likely does not exceed ~20% of the total reaction rate. Theory alone cannot provide precise yield estimates, due to uncertainties in key parameters, that is, precise barrier heights, average energy losses per collision, and the singlet ↔ triplet ISC rate that impacts methanol production.

Fortunately, atmospheric measurements provide valuable constraints. The persistent model underestimation of CH₃OH measurements over the remote Pacific cannot be explained by ocean/atmosphere exchanges, since higher emissions would cause strong decreasing vertical gradients not seen in campaign data; on the contrary, eddy covariance measurements indicate that oceanic emissions might be very low. Another remote source of methanol, the photochemical production due to CH₃O₂ + RO₂ reactions, could be underestimated. But since it is largely dominated by the CH₃O₂ self-reaction of which the methanol yield (~0.63) cannot be much underestimated, and since CH₃O₂ production from CH₄ + OH is also well constrained, only a large production of organic peroxy radicals from non-methane organic precursors could boost this source of methanol. High observed acetaldehyde over oceans suggested indeed the existence of unknown sources of CH₃CHO or of its precursors. However, besides the noted inconsistency of those observations with measured PAN:NOx ratios, the good agreement of modelled CH₂O with observations over oceans (Supplementary Fig. 12) shows that those potential sources cannot weigh heavily on CH₂O and CH₂O₂ production.

The only viable candidate for the missing remote source of methanol is therefore CH₃O₂ + OH, with an overall methanol yield crudely estimated to be ~30%, consistent with theoretical estimates given their uncertainties. Given the experimental uncertainty (50%) in the total rate constant of the reaction, this inferred overall yield could be even higher, or possibly lower. The total photochemical source of methanol in run C (130 Tg per year) slightly exceeds the range (50–100 Tg per year) estimated by Jacob et al., because of a higher net ocean sink and lower continental emissions in our simulations. The contribution of CH₃O₂ + OH (115 Tg per year globally) is comparable in magnitude to the total terrestrial emission source. Further work will be needed to evaluate how this source will impact our understanding of the methanol budget. Clearly, a better understanding of ocean-atmosphere exchanges is required to refine the top–down yield estimation presented above. It is not currently possible to determine which of the direct methanol formation channel or indirect pathway through the stabilised TROI X is dominant. A more direct experimental determination is obviously needed. Hopefully TROI X can be measured, although loss to walls might prove challenging, and atmospheric concentrations should be very low, a few pptv at most.

Reaction with OH might be also significant for other peroxy radicals, such as those formed from biogenic terpenoids. We expect that for the much larger activated ROOOOH, conversion to a complex RO—HO₂ and eventual dissociation to RO + HO₂ will be substantially slower than for CH₃OOOH.
such that collisional stabilisation of ROOOH should be a major if not dominant product route. However, the global relevance for large peroxys formed from biogenic terpenoids is expected to be lower compared with CH$_3$O$_2$ + OH, because OH levels are generally lower in the boundary layer over forests than in the oceanic lower troposphere, and because the reaction of HO$_2$ with large peroxys is considerably faster than the reaction of CH$_3$O$_2$ with OH$_2$ (ref. 40). Assuming a rate constant similar to that of CH$_3$O$_2$ + OH, the reaction of large biogenic peroxy radicals with OH is estimated here to account for ~3% of their total sink over remote forests.

**Methodology**

**Quantum chemistry.** All the structures presented on the potential energy surface were fully optimized with DFT using the MO6-2X-D3/6-311 + + G(3df,3pd) level of theory in Gaussian 09 version D.01 (ref. 41; see Supplementary Table 7), except where explicitly stated otherwise. The MO6-2X-D3 method was benchmarked and recommended for the general main group elements including the evaluation of thermochemistry, kinetics and noncovalent interactions. For the geometry optimization and the corresponding frequency calculations, a tight convergence criterion and a superfine integration grid (150,974) were adopted. Wherever appropriate, an unrestricted ansatz was used, and careful checks were made to ensure that low-spin open-shell solutions were found to the Kohn–Sham equations. The calculated vibrational frequencies have been used for evaluation of zero-point energy corrections. All the transition states for the reactions involving the abstraction or transfer of a hydrogen atom were confirmed by IRC calculations, while for the reactions from the reactant complex $^{1}$RC via TRIOX to the product complex $^{1}$PC, attempts to generate IRC curves failed due to the low curvature of the potential energy surface, so instead, various scans were used to explore the behavior of those two loose TSs (Supplementary Fig. 3 and Supplementary Note 1).

Various single-point calculations were carried out using CASSCF, CASPT2 and CCSD(T)-F12. The CASSCF and CASPT2 calculations were performed with Molpro 2012.11 (refs 43,44) with an active space of 18 electrons in 13 active orbitals (which corresponds to a full-valence active space, but omitting the O–H and C–H bonding orbitals and the C–H anti-bonding orbitals), with the cc-pVTZ basis set. We also calculated the spin–orbit coupling constant with Molpro at CASSCF(18,13)/cc-pVTZ level of theory.

Explicitly correlated CCSD(T)-F12 energies were obtained with the ORCA 3.03 package, using an unrestricted HF-reference wavefunction for reactant and product radicals and the open-shell singlet intermediates, and a restricted reference otherwise. The cc-pVTZ-F12 basis set and appropriate auxiliary basis sets were used. Unless mentioned otherwise, all reported energies derive from CCSD(T)-F12/cc-pVTZ-F12 calculations with ZPVE corrections from MO6-2X-D3/6-311 + + G(3df,3pd).

**Theoretical reaction kinetics.** The statistical-kinetics rates for thermal as well as chemically activated reactions were estimated using the energies obtained at our highest level and including the ZPVE (scaled by a factor 0.97 (ref. 48)) as stated above, while partition functions or integrated sums of vibrations states and vibration state densities were based on the MO6-2X-D3 harmonic vibration frequencies (scaled by a factor 0.983 (ref. 48)) and rigid rotor rotation constants. For all structures and transition states involved we adopted the harmonic oscillator approximation, commensurate with our aim of identifying the relevant reaction pathways and distinguishing between major and minor routes based on an approximate, semi-quantitative assessment of end-product yields.

As detailed in the Results section, the only thermal bimolecular reaction that needs to be considered was found to be unimportant if not negligible. Its thermal rate coefficient at 298 K was computed using conventional transition state theory, with tunnelling factor estimated assuming an asymmetric Eckart potential (ref. 49,50).

The majority of the relevant reaction steps are chemically activated unimolecular reactions (the initial single closed-open complex $^{1}$RC to the closed-shell singlet intermediate TRIOX and (iii) the resulting product complexes $^{1}$PC and $^{3}$PC). We employed RRKM theory, to estimate the micro-canonical rate coefficients for each of the steps:

$$k(E) = \frac{a \times G^\ast}{E - E^\ast} \left(\frac{k_B T}{h N(E)}\right)^n$$

in which $x$ is the reaction path degeneracy, $h$ Planck’s constant, $E^\ast$ the TS energy, $E$ the vibration energy of the reacting activated intermediate, $N(E)$ its density of vibrational states and $G^\ast$ the sum of the accessible vibration states of the TS; both the latter were evaluated by exact count (ref. 22). The conservation of angular momentum was accounted for in reasonable approximation by correcting the potential energies (inclusive ZPVE) of the activated reactants and transition structures by their average rotation energy relative to that of the reactant complex $^{1}$RC. The approximations used for the stepwise reaction in the RRKM rate constant calculation of the initial complex $^{1}$RC is < 1 ps, the original thermal distribution $F_{\text{Th,v}}$ remains conserved up to the TRIOX intermediate, but it shifts down for $^{1}$PC and $^{3}$PC by ~ 0.45 kcal mol$^{-1}$ at 298 K/1.013 bar, ~ 0.35 kcal mol$^{-1}$ at 285 K/750 bar and ~ 0.25 kcal mol$^{-1}$ at 256 K/400 bar, respectively, due to the average of ~ 0.5, 0.4 and 0.3 collisions, at TRIOX at net rate above, thermally, that is at ~ 0.3 ps. See < $\xi$ ($k_{\text{Th,v}}$) values in Table 2>. The lifetime of ~ 0.3 ps of $^{1}$PC and $^{3}$PC is too short for further collisional losses. The width of $F_{\text{Th,v}}(E_o)$, of ~ 2 kcal mol$^{-1}$, is much less than the average excess energy ($E - E^\ast$) for most reaction steps, and the $k(E)$ are generally not far from their high-energy asymptotes, such that the $F_{\text{Th,v}}(E_o)$ averaged $k(E_o) - k(E^\ast)$ differ only 1–20% from $k(E^\ast)$. The only exception is the $^{1}$PC reaction through TS2, which anyway is negligibly slow compared with the competing reaction through TS1. As a result, the precise shape of $F_{\text{Th,v}}$ is of little importance for the overall kinetics of the chemically activated unimolecular reactions of our systems, though the average value of the thermal $k_{\text{Th,v}}(E_o)$ is of importance for the temperature barrier and balance.

Given the initial excess energy of 4 kcal mol$^{-1}$, the reaction timescale for $^{1}$PC through TS1 at net rate $k(E_o)$ (~0.97 × $k_{\text{Th,v}}$ due to the reverse reaction), the Lennard–Jones collision frequency of CH$_3$OH with air molecules, $k_{\text{coll}} = 4 \pi \rho r^2[M]$, is estimated to be about 1.2, 0.92 and 0.57 × 10$^{12}$ s$^{-1}$ at 298 K/1.013 bar, 285 K/750 bar and 256 K/400 bar, respectively. The biradical energy transfer model of Troe was used and implemented in a quasi-stochastic approach; the average energy transferred per collision, a critical quantity for the overall $k_{\text{coll}}$ but highly uncertain, was assumed to be $<\Delta E_o>$ ~ 1 kcal mol$^{-1}$, amounting at 298 K to an average energy lost per down-collision $\zeta \approx 1.34$ kcal mol$^{-1}$ and average energy gained per up-collision $\eta \approx 0.44$. For a given initial energy $E_{\text{th,v}}$ of $^{1}$PC, the stabilization fraction was found as the ratio of the product of the successive, increasing probabilities of a (new) collision at constant rate $k_{\text{coll}}$ in competition with TRIOX → $^{1}$PC rearrangement at net rate $k^\ast(E_{\text{th,v}})$ that decreases on average after each collision:

$$f_{\text{stab}}(E_{\text{th,v}}) = \prod_{n=1}^{N} \left(\frac{k_{\text{coll}}}{k^\ast(E_{\text{th,v}})}\right)$$

With the initial excess energy of 47 kcal mol$^{-1}$, this product converges rapidly after some 8–10 collisions for the adopted $<\Delta E_o>$, with $<\Delta E_o>$ below 1 kcal mol$^{-1}$.

Overall and net reaction rates and end-product yields were obtained in a straightforward way by duly considering the fractional contribution of each competing reaction for each intermediate in the complete scheme.
oceanic source of 39 Tg (in 2010) and an oceanic uptake represented as dry deposition (between 46 and 66 Tg per year depending on the model simulation). The isoprene degradation mechanism has been updated to account for the revised peroxy radical kinetics of the Leuven Isoprene Mechanism LIM1 (ref. 56) as well as for the chemistry of isoprene epoxides37,38. Wet scavenging is parameterized based on ECMWF cloud and precipitation fields39. Dry deposition follows Wesely’s resistance-in-series scheme40, with aerodynamic resistances based on Monin-Oblukhov similarity theory (ECMWF, IFS Documentation—Cy40r1, Operational implementation 22 November 2013, Part IV: Physical processes, European Centre for Medium-Range Weather Forecasts, Shinfield Park, Reading, England, 2014.) using sensible heat fluxes and friction velocities from ECMWF operational analyses and quasi-laminar layer resistances dependent on gas-phase diffusivity.41 Surface resistances are calculated depending on mesophyll, cuticular, ground and in-canopy aerodynamic resistances.52,61,62 The surface resistances are adjusted to provide a better match of modelled dry deposition velocities with eddy-covariance estimates over a forest by Nguyen et al.;43 in particular, the H2O2 surface resistance becomes negligible after this adjustment.

As detailed in Subsection IV B, the reactions of the stabilized tetroxide include the thermal conversion to the product complex 1PC; reaction with OH; reaction with the water dimer; and reactive uptake on aqueous aerosols. Aerosol uptake is calculated44 based on sulfate/ammonium/nitrate and carbonaceous aerosols calculated by IMAGES, and sea salt aerosols obtained from the MACC (Monitoring Atmospheric Composition & Climate) Reanalysis (apps.ecmwf.int/datasets/data/macc-reanalysis/levtype=sfc/). The water dimer concentrations are calculated using an equilibrium constant expression validated with available experimental data.

Data availability. The authors declare that the data supporting the findings of this study are available within the article and its Supplementary Information file. Any further relevant code and data used in the paper are available from the authors upon request.

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Author contributions
J.F. and J.N.H. designed and supervised the theoretical calculations; Z.L., V.S.N. and J.P. performed the theoretical calculations; J.-F.M. designed the model calculations and analysed the results; J.-F.M. and T.S. performed the model calculations; all authors discussed the theoretical and modelling results; J.-F.M., J.P., Z.L. and J.H. wrote the manuscript.

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