

Criegee + HONO reaction: a bimolecular sink of Criegee, and the missing non-photolytic source of OH[•]

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Abstract. One of the most important puzzles in atmospheric chemistry is a mismatch between observed and modelled concentrations of OH[•]/HO₂[•] in the presence of high concentration of volatile organic compounds. It is now well established that to fulfill this gap, one needs a reaction that is not only capable of producing OH[•] but also able to act as a sink of HO₂[•]. In the present work, we are proposing the Criegee + HONO reaction as a possible solution of this puzzle. Our quantum chemical and kinetic calculations clearly suggest that this reaction can not only be an important source of OH radical but can also act as a sink of HO₂ radical. Our study also suggests that HONO has the potential to act as a bimolecular sink of Criegee intermediates, and for some Criegee intermediates under certain atmospheric condition it can even surpass the traditionally known bimolecular sinks such as SO₂ and water dimer, even in high humid conditions.

1 Introduction

It is well-known that the atmospheric chemistry is mainly dominated by the radicals (Anderson, 1987; Monks, 2005). Particularly in the troposphere, these radicals are key in degrading various pollutants, a phenomenon as important as the ozone layer for the existence of life (Weinstock, 1969; Lelieveld et al., 2004). The primary radicals responsible for the oxidative power of troposphere come from the HO_X (OH[•], HO₂[•], RO[•], RO₂[•] etc.) family (Prinn, 2003; Ehhalt, 1987; Khan et al., 2018). Among them, OH[•] is considered as the most important oxidant in the troposphere (Lelieveld et al., 2002, 2016). Although OH[•] is the most studied radical in the atmosphere, there are still open questions regarding its sources in the atmosphere (Heald and Kroll, 2021; Yang et al., 2024). For a long time, it was believed that OH radicals are mainly formed in daytime via photolysis of tropospheric ozone (O₃), and nitrous acid (HONO) (Calvert et al., 1994; Alicke et al., 2003; Griffith et al., 2016; Aumont et al., 2003). But now, with various on-field measurements (Geyer et al., 2003; Ren et al., 2003; Emmerson and Carslaw, 2009), it is well established that OH radicals are also present at night in sufficient amounts. In fact, average nighttime concentration of OH[•] ($\sim 2.6 \times 10^5$ molecule cm⁻³) is only one order of magnitude lower than its average daytime concentration ($\sim 1.9 \times 10^6$ molecule cm⁻³) (Emmerson and Carslaw, 2009). As the lifetime of OH[•] is only ~ 1 second, this much concentration of OH[•] during night indicates its *in situ* generation via non-photolytic sources. The major non-photolytic source of OH[•] is the recycling of HO₂[•] radicals (Whalley et al., 2011; Stone et al., 2012; Hofzumahaus et al., 2009; Smith et al., 2006; Hens et al., 2013). Specifically, during the daytime, the primary reaction contributing to this recycling process is NO[•] + HO₂[•], whereas at night, the key reaction is NO₃[•] + HO₂[•] (Hall et al., 1988; Mellouki et al., 1988, 1993; Rai and Kumar, 2024). However, compared to photolytic sources, non-photolytic sources of OH[•] remain less understood in atmospheric chemistry (Brown and Stutz, 2012; Emmerson and Carslaw, 2009). This is evidenced by the fact that, in the atmosphere with a high concentration

of volatile organic compounds (VOCs), atmospheric models consistently under-predict the concentration of OH• compared to the observed value (Emmerson and Carslaw, 2009; Stone et al., 2012). This discrepancy is especially pronounced in winter (Harrison et al., 2006; Heard et al., 2004; Slater et al., 2020) and indoor environments (Østerstrøm et al., 2025; Gomez Alvarez et al., 2013; Reidy et al., 2023), where light plays a minimal role. In addition, the discrepancy between measured and observed value of OH• was also found to depend upon NO_X concentration. Both under low NO_X (Carslaw et al., 2001; Tan et al., 2001; Lelieveld et al., 2008; Tan et al., 2017) as well as high NO_X (above 6 ppbv) (Slater et al., 2020), the discrepancy was found to be quite significant. As the primary recycling of HO₂• to OH• occurs via NO_X, the under-prediction of OH• by models under low NO_X conditions suggests either the presence of another route for recycling or some new non-photolytic source of OH•. This hypothesis is further strengthened by a few combined experimental and modelling studies. For example, Lu et al. (Lu et al., 2012) have to introduce an artificial source of OH• ↔ HO₂• inter-conversion (RO₂• + X → HO₂•, HO₂• + X → OH•) in their atmospheric model to match the experimental concentration profile. In another study, to match the experimental OH concentration with models, Whalley et al. (Whalley et al., 2011) increased the concentration of VOCs in their model. Although their computed OH• concentration becomes closer to experimental value, the mismatch between observed and measured concentration of HO₂• becomes worse. There have been various attempts to identify the missing source of OH• in the atmosphere (Paulot et al., 2009; Peeters et al., 2014; Sander et al., 2019). For example, Peeters et al. (Peeters et al., 2009; Peeters and Müller, 2010; Peeters et al., 2014) suggested that the oxidation of isoprene can regenerate HO_X radicals in the presence of light via isoprene-peroxy radical interconversion and isomerisation pathways (Leuven Isoprene Mechanism (LIM)). Although the introduction of LIM into chemical models were found to improve the value of modelled OH• concentration, the modelled values still remain under-predicted (Crounse et al., 2011; Teng et al., 2017; Berndt et al., 2019; Novelli et al., 2020; J. Medeiros et al., 2022). Particularly, the LIM is more effective in regions where biogenic volatile organic compounds (BVOCs) dominate and NO_X concentration is ultra low, e.g. rain forest regions (Whalley et al., 2011; Feiner et al., 2016; Lew et al., 2020). In contrast, in regions where sufficient anthropogenic sources of VOCs are present, e.g. in polluted areas, LIM is not effective. In addition, LIM is not fundamentally a HO₂• to OH• interconversion process, rather it is the recycling of VOCs to OH•. In a recent study, Yang et al. (Yang et al., 2024) suggested that aldehyde could be an additional source of OH•. Authors proposed that the autoxidation of carbonyl organic peroxy radicals (R(CO)O₂) derived from higher aldehydes, can produce OH• through photolysis (RAM mechanism). Though RAM mechanism efficiently predicts OH• production at low NO_X concentrations, it still under-predicts the same at high NO_X concentrations. Interestingly, when both LIM and RAM are incorporated into a base model in the presence of moderate concentration of NO_X, OH• concentration improves significantly, but the discrepancy in the modelled and observed HO₂• remains unresolved. It is also worth mentioning that photolysis is an important part of both, LIM and RAM, and hence, both of these mechanism do not offer any help in improving the model OH• concentration in nocturnal environment. Furthermore, both LIM and RAM are also not directly involved in recycling of HO₂• to OH•. The discrepancy in the model occurs during both day and night (Faloona et al., 2001; Hens et al., 2013; Geyer et al., 2003), and is associated with HO₂• to OH conversion (Whalley et al., 2011; Hofzumahaus et al., 2009). In light of these studies, we believe that the puzzle of missing OH• source is very much alive and the key to this puzzle may be a non-photolytic source capable of HO₂• ↔ OH• recycling.

In the present work, we are proposing reaction of Criegee intermediate with HONO as a source of OH[•]. Criegee Intermediates (CIs) are formed during the ozonolysis of alkenes (Criegee, 1975; Johnson and Marston, 2008; Taatjes, 2017). In fact, alkene ozonolysis is a highly exothermic reaction produces energized CIs. Some of the energized CIs readily convert into OH[•] via unimolecular decomposition, while the remaining CIs get collisionally stabilized (sCI) (Horie and Moortgat, 1991; Donahue et al., 2011; Novelli et al., 2014; Alam et al., 2011). sCIs can undergo either a thermal unimolecular dissociation or a bimolecular reaction. Depending upon concentration of the co-reactant and rate constant of such bimolecular reaction, the bimolecular reaction paths can be the main sink of sCI (Osborn and Taatjes, 2015; Lin et al., 2015; Sheps et al., 2014; Vereecken and Francisco, 2012). There are several studies in the literature that suggest CI reacts rapidly with the trace gases present in the atmosphere (Cox et al., 2020; Mallick and Kumar, 2020; Vereecken et al., 2015; Long et al., 2016, 2021). In this work, we are suggesting HONO as a new partner for the bimolecular reaction of Criegee intermediates that is capable of producing OH radicals. The concentration of CI ($\sim 10^4 - 10^5$ molecule cm^{-3}) in the atmosphere is comparable with Cl[•] ($\sim 5.0 \times 10^4 - 3.0 \times 10^5$ molecule cm^{-3}) and OH[•] ($\sim 1.0 \times 10^5 - 4.0 \times 10^6$ molecule cm^{-3}) (Khan et al., 2018; Novelli et al., 2017). Similarly, nitrous acid (HONO) is also an important trace gas present in the nighttime atmosphere in a considerable amount (Li et al., 2021; Song et al., 2023). The average concentration of HONO is $\sim 8.9 \times 10^{10}$ molecule cm^{-3} , which can reach as high as $\sim 6.9 \times 10^{11}$ molecule cm^{-3} during the fog event (Pawar et al., 2024). Although a general wisdom about HONO is, its concentration builds up in nighttime, and in daytime, it decomposes via photolysis to give OH[•], HONO itself is a highly reactive molecule and can participate in various bimolecular chemical reactions during night (Anglada and Sole, 2017; Lu et al., 2000; Wallington and Japar, 1989). Moreover, in indoor environments, high concentrations of OH[•] have been found to strongly correlate with high concentrations of HONO (Gomez Alvarez et al., 2013). It is important to mention that, the reaction of HONO with the simple Criegee intermediate (CH₂OO) has already been investigated theoretically (Kumar et al., 2022). In that investigation, the major product was predicted to be hydroperoxymethyl nitrite (HPMN). We will show in the present work that the main product of this reaction is OH[•] and this newly found path is the dominant path of the title reaction.

2 Methodology

2.1 Electronic structure theory

There are two parts of electronic structure theory; optimization and subsequent single-point energy calculations. The criteria behind choosing a method for optimization is; it should be computationally not very demanding and at the same time, it should accurately predict the geometries and frequencies of the species involved in the reaction. Based on these criteria, in the present work, the CCSD(T)/CBS//M062X/aug-cc-pVTZ level of theory was chosen, which is known to give reasonable results in various previous studies (Kumar et al., 2022; Vereecken et al., 2017, 2014; Vereecken, 2017) for reactions involving Criegee intermediates. Gaussian16 software package (Frisch et al., 2016) has been used to carry out all the optimization and single-point energy calculations. To estimate energies at CCSD(T)/CBS level of theory, first, we calculated the single point energies at CCSD(T)/aug-cc-pVDZ, and CCSD(T)/aug-cc-pVTZ level of theory, and then extrapolated these energies to corresponding CBS limit using the method of Varandas and Pansini (Varandas and Pansini, 2014; Pansini et al., 2016) (see ESI for the details).

97 Energetics calculations shed light only on enthalpic requirement of the reaction, for a barrierless process, entropy is an equally
 98 important factor. Therefore, to account for both, enthalpy and entropy, we have estimated the rate constant for $\text{CH}_2\text{OO} +$
 99 HONO reaction within a temperature range of 213–320 K.

100 The mechanism of $\text{CH}_2\text{OO} + \text{HONO}$ reaction can be represented by following reaction:



102 To calculate the overall rate constant of the title reaction, we have used the master equation approach as implemented in
 103 the MESMER software package. The reaction R1 proceeds in three steps. In the first step, the formation of RC occurs via
 104 a barrierless association of isolated reactants. MESMER uses the inverse-Laplace-transform (ILT) method to estimate the
 105 energy-dependent rate constant, $k(E)$, for this step. This, in turn, requires fitted Arrhenius parameters as input to MESMER,
 106 which are obtained using KTOOLS code as implemented in the MultiWell suite of programs (Barker et al., 2021). KTOOLS
 107 uses variational transition state theory (VTST) for the barrierless reaction. The inputs for KTOOLS are energies and frequen-
 108 cies calculated on potential energy surface (PES) scans along the coordinate describing the dissociation of RC into isolated
 109 reactants. Each point on the PES serves as a trial transition state; KTOOLS searches for the transition state for which the
 110 reaction flux is minimized. In the present work, we have obtained this PES scan at CCSD(T)/CBS//M062X/aug-cc-pVTZ level
 111 of theory (Table S9 of the ESI contains the energy as well as frequencies at each scan points). In the next step, RC under-
 112 goes unimolecular dissociation to PC via a transition state. MESMER uses Rice-Ramsperger-Kassel-Marcus (RRKM) theory,
 113 including tunneling contributions via an unsymmetrical Eckart barrier to compute the unimolecular reaction rate. In the final
 114 step, PC spontaneously dissociates to form isolated products. It is important to mention that we do not find any tight tran-
 115 sition state for product formation from PC; therefore, we have treated this step also using ILT assuming that rate constants
 116 are independent of temperature. The obtained rate constants within 213–320 K were then fitted with Arrhenius equation and
 117 supplied to the MESMER. It is worth noting that the reactant complex (RC) and the transition state (TS) exhibit hindered ro-
 118 tational motions, and multiple conformations may exist due to different torsional angles. To account for this, we have used the
 119 HinderedRotorQM1D model in MESMER to compute rate constants. Specifically, we performed a one-dimensional potential
 120 energy scan of OH torsion along the N–O bond in both RC and TS at CCSD(T)/CBS//M062X/aug-cc-pVTZ level of theory,
 121 that covers the full 0° to 360° range. The resulting energy profiles are used to calculate the hindered rotor partition functions.
 122 During this scan, we found local minima in both RC and TS, suggesting that our originally optimized structures correspond to
 123 the global minimum conformers. To verify this, we also manually searched for other possible minimum conformers and again
 124 found that our original structures are global minimum conformers. The Lennard-Jones (L-J) model is used to calculate the
 125 collision frequency between reactants and the bath gas. To obtain the L-J parameters for RC, we performed a PES scan along
 126 the reaction coordinate separating bath gas from RC, and fitted the obtained PES with the 12-6 L-J potential expression. The
 127 fitted L-J parameters for RC turn out to be, $\sigma = 3.1 \text{ \AA}$ and $\epsilon = 895.5 \text{ K}$. A single-exponential down model is used to describe
 128 the collisional energy transfer probability with a maximum energy grain size of 100 cm^{-1} and $\Delta E_{down} = 150 \text{ cm}^{-1}$.

130 In the present work, we have investigated the reactions of Criegee intermediates (CIs) with nitrous acid (HONO). It is known
131 that the reactivity of CI is greatly influenced by the substitution group present on carbon center of the CI. Therefore, to account
132 for it, we have studied two types of CIs; the simplest Criegee intermediate (CH_2OO) and the dimethyl-substituted Criegee in-
133 termediate ($(\text{CH}_3)_2\text{COO}$). Another motivation for choosing $(\text{CH}_3)_2\text{COO}$ comes from the fact that in contrast to simple Criegee
134 which is formed only from the ozonolysis of ethene, the dimethyl-substituted Criegee intermediate can be generated from the
135 ozonolysis of many highly abundant alkenes, such as terpenes and mycrene, and hence, the concentration of $(\text{CH}_3)_2\text{COO}$ is
136 significantly higher in the atmosphere. In this section, we will first discuss the energetics and kinetics of $\text{CH}_2\text{OO} + \text{HONO}$
137 reaction, followed by $(\text{CH}_3)_2\text{COO} + \text{HONO}$ reaction.

138 The potential energy surface for $\text{CH}_2\text{OO} + \text{HONO}$ reaction is depicted in Figure 1. It is evident from Figure 1 that reaction
139 occurs in three steps; in the first step, CH_2OO interacts with H atom of HONO via hydrogen bonding and forms a stable
140 reactant-complex (RC1), which is $\sim 10.1 \text{ kcal mol}^{-1}$ stable than isolated reactants. In the next step, RC1 undergoes a uni-
141 molecular transformation to form product-complex (PC1) which has stabilization energy of $\sim -44.7 \text{ kcal mol}^{-1}$ with respect to
142 the isolated reactants. This happens via a transition-state (TS1) that is effectively $\sim 8.0 \text{ kcal mol}^{-1}$ below the isolated reactants.
143 In the last step, PC1 undergoes unimolecular dissociation to form final products, i.e., CH_2O , $\text{OH}^\bullet$, and NO_2 . Gibbs free energy
144 at 298 K associated with this conversion of PC1 to isolated products is $\sim -2.5 \text{ kcal mol}^{-1}$ (shown in Figure S2 of ESI), which
145 suggests that the formation of $\text{OH}^\bullet$ via $\text{CH}_2\text{OO} + \text{HONO}$ reaction is a spontaneous process. The overall reaction was found
146 to be exothermic by $\sim 17.3 \text{ kcal mol}^{-1}$ that lies close to the experimental value of $\sim 16.9 \text{ kcal mol}^{-1}$ (Ruscic and Bross,
147 2021), again confirming the adequacy of the methodology used. The computed bimolecular rate constant values ($k_{bi}^{CH_2OO}$) for
148 $\text{CH}_2\text{OO} + \text{HONO}$ reaction in the temperature range 213–320 K are given in Table 1. It is evident from Table 1 that the values
149 of $k_{bi}^{CH_2OO}$ slightly decrease with increasing temperature, a typical character of a barrierless process. For example, at 213 K,
150 values of $k_{bi}^{CH_2OO}$ is $\sim 1.17 \times 10^{-11} \text{ cm}^3 \text{ molecule}^{-1} \text{ sec}^{-1}$ which becomes $\sim 6.3 \times 10^{-12} \text{ cm}^3 \text{ molecule}^{-1} \text{ sec}^{-1}$ at 320 K.

151 Figure 2 depicts the potential energy surface of $(\text{CH}_3)_2\text{COO} + \text{HONO}$ reaction. It is evident from Figure 2 that $(\text{CH}_3)_2\text{COO}$
152 + HONO reaction also proceeds in three steps; in the first step, $(\text{CH}_3)_2\text{COO}$ associates with HONO to form a stable reactant-
153 complex (RC2) that is $\sim 14.2 \text{ kcal mol}^{-1}$ more stable than isolated reactants. Next, RC2 transforms into product-complex
154 (PC2) having stabilization energy of $\sim -36.2 \text{ kcal mol}^{-1}$ with respect to isolated reactants. This transformation occurs through
155 a transition state that lies $\sim 10.1 \text{ kcal mol}^{-1}$ below the isolated reactants. At last, PC2 undergoes unimolecular dissociation to
156 form final products, i.e., $(\text{CH}_3)_2\text{CO}$, $\text{OH}^\bullet$, and NO_2 . Here also, the Gibbs free energy at 298 K associated with the conversion
157 of PC2 to isolated products is $\sim -6.3 \text{ kcal mol}^{-1}$ (Figure S2 of the ESI), making the overall product formation spontaneous.
158 Using the energetics, we have also computed the rate constant for $(\text{CH}_3)_2\text{COO} + \text{HONO}$ reaction employing master equation
159 in the same 213–320 K temperature range. The calculated bimolecular rate constants ($k_{bi}^{(CH_3)_2COO}$) are listed in Table 1. It
160 is evident from Table 1 that similar to $\text{CH}_2\text{OO} + \text{HONO}$ reaction, here also the values of $k_{bi}^{(CH_3)_2COO}$ slightly decrease with
161 increasing temperature across the whole range of temperature. But the bimolecular rate constant of $(\text{CH}_3)_2\text{COO} + \text{HONO}$ re-
162 action becomes ~ 2.6 to 3.6 times higher compared to the same for $\text{CH}_2\text{COO} + \text{HONO}$ reaction at all temperatures considered

163 in the present work. For example, at 298 K, the value of $k_{bi}^{(CH_3)_2COO}$ is $\sim 2.03 \times 10^{-11}$ cm³ molecule⁻¹ sec⁻¹, whereas the
 164 value of $k_{bi}^{CH_2OO}$ is only $\sim 7.2 \times 10^{-12}$ cm³ molecule⁻¹ sec⁻¹. It is worth noticing that, while computing the bimolecular rate
 165 constant, the capture rates of both the reactions are almost same (Table S3 of the ESI). The difference in the rate values of
 166 the two reactions depends on whether the reactant complex will proceed forward or backward, which further depends on the
 167 forward and backward Gibbs free energy barriers of the reactant complex. The Gibbs free energy profile at 298 K is shown
 168 in Figure S2 of the ESI. It is evident from Figure S2 that due to the higher stabilization of RC2 (corresponding to dimethyl-
 169 substituted CI), its reverse free energy barrier is high (~ 2.9 kcal mol⁻¹), while the same is very low for RC1 (corresponding
 170 to simplest CI) (~ -1.3 kcal mol⁻¹). Consequently, the relative yields of product are higher for the (CH₃)₂COO + HONO
 171 reaction compared to CH₂COO + HONO reaction.
 172 Lastly, it is important to discuss the uncertainties associated with the computed rate constant due to limitations in the method-
 173 ology (Fernández-Ramos et al., 2006). For example, a major source of uncertainty can originate from the fact that Criegee
 174 intermediates are known to possess moderate multireference character, and CCSD(T)/CBS sometimes fails in accurately pre-
 175 dicting the energetics of such reactions (Rai and Kumar, 2022; Mallick et al., 2019; Mallick and Kumar, 2018). It is worth
 176 mentioning that for multireference systems, incorporating higher-level excitations at the coupled-cluster level yield energet-
 177 ics within chemical accuracy (Tajti et al., 2004; Misiewicz et al., 2018; Nguyen et al., 2013; Anand and Kumar, 2023; Rai
 178 and Kumar, 2023). To assess the uncertainty in the energetics arising from the multireference character, we have carried out
 179 CCSDT(Q)/CBS calculations for the smaller Criegee intermediate reaction, i.e., CH₂OO + HONO. We focused on key station-
 180 ary points; the reactant complex (RC) and the transition state (TS). The various components of the post-CCSD(T) corrections
 181 (δ_T and $\delta_{T(Q)}$) are provided in Table S7 of the ESI. It is evident from Table S7 that post-CCSD(T) corrections lead to only mi-
 182 nor changes in the calculated energetics of CH₂OO + HONO reaction. Quantitatively, these corrections reduce the stabilization
 183 energy of RC by ~ 0.54 kcal mol⁻¹, while increasing the barrier height by a similar ~ 0.67 kcal mol⁻¹. Both variations fall
 184 well within the range of chemical accuracy. Furthermore, we have also estimated the capture and bimolecular rate constants
 185 using post-CCSD(T) energetics (see Table S8 of ESI), which suggest that at 298 K, the bimolecular rate constants calcu-
 186 lated at post-CCSD(T) and CCSD(T)/CBS levels are almost similar (5.53×10^{-12} and 7.21×10^{-12} cm³ molecule⁻¹ sec⁻¹,
 187 respectively). This supports the reliability and computational efficiency of our chosen level of theory, CCSD(T)/CBS//M06-
 188 2X/aug-cc-pVTZ, for studying the title reaction. Another source of uncertainty in the computed rate constant may arise from
 189 the error in estimation of frequency. Such errors in frequency estimation may lead to 2σ (± 2 kcal mol⁻¹) uncertainties in
 190 the computed barrier heights. To account for this, we have assumed an uncertainty of ± 2 kcal mol⁻¹ in both well depths and
 191 reaction barriers. Using this assumption, we estimated the resulting uncertainty in the rate constants at 213 K and 298 K for the
 192 model reaction CH₂OO + HONO. Due to ± 2 kcal mol⁻¹ uncertainty in the reaction barriers and well depths, the deviation in
 193 the rate constant at 213 K is $\sim 1.17_{-0.84}^{+1.8} \times 10^{-11}$ cm³ molecule⁻¹ sec⁻¹ (± 2 kcal mol⁻¹ reaction barriers) and $\sim 1.17_{-0.08}^{+0.08} \times$
 194 10^{-11} cm³ molecule⁻¹ sec⁻¹ (± 2 kcal mol⁻¹ well depths), respectively. At 298 K, the same becomes $\sim 7.21_{-5.12}^{+11.04} \times 10^{-12}$
 195 cm³ molecule⁻¹ sec⁻¹ (± 2 kcal mol⁻¹ reaction barriers) and $\sim 7.21_{-0.72}^{+0.72} \times 10^{-12}$ cm³ molecule⁻¹ sec⁻¹ (± 2 kcal mol⁻¹
 196 well depths), respectively. This study suggests due to 2σ error in the barrier height, there can be an error of a $\sim$ factor-of-two
 197 in the estimated rate constant values. Our analysis also suggests that the uncertainty in the rate constant estimation is much

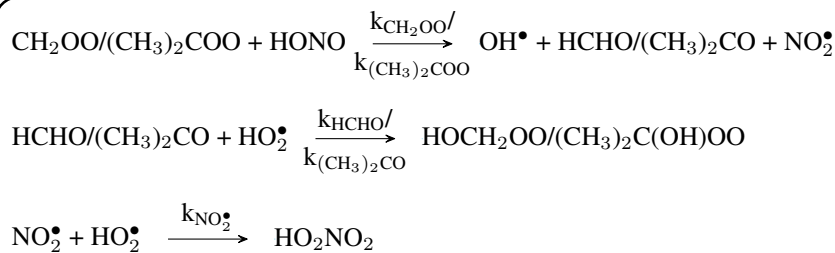
lower at low temperature region compare to high temperature regions. In addition, in the estimation of the partition function, the rigid rotor harmonic oscillator (RRHO) approximation is employed, which again can introduce some error in the final rate constant. For a typical 2σ error, the uncertainty arising from the RRHO approximation can also contribute approximately a factor-of-two uncertainty in the evaluated partition function ratios.

4 Atmospheric implications

After estimating the energetics and kinetics of title reaction, it is important to discuss the impact of title reaction in the atmospheric chemistry. The importance of title reaction in the atmosphere critically depends on how it competes with other known sinks of Criegee intermediate, i.e., H_2O , $(\text{H}_2\text{O})_2$, NO_2 , NO , CO , and SO_2 . The efficiency of a chemical reaction in the atmosphere depends upon two factors; rate of reaction and concentration of co-reactants. The effective rate constant (k_{eff}) captures both of these factors as it is defined as the multiplication of bimolecular rate and concentration of co-reactants. Therefore, we have used k_{eff} to compare the effectiveness of title reaction compared to other sinks of Criegee intermediates. A list of effective rates for the reaction of CI with H_2O , $(\text{H}_2\text{O})_2$, NO_2 , NO , CO , and SO_2 at 298 K are provided in Table S4 of the ESI. To compute k_{eff} , the average concentrations of all the sinks have been taken from polluted urban environments. The corresponding rate coefficients of all the sinks are taken from experimental measurements. One can see from Table S4, the effective rate coefficients (k_{eff}) of CO , NO , and NO_2 are lower compared to those of SO_2 , H_2O , and $(\text{H}_2\text{O})_2$. For example, k_{eff} for the reaction of CI with SO_2 is 3.35 sec^{-1} , while that for NO_2 is only 0.9 sec^{-1} . Therefore, in the present work, we have focused our attention on a detailed comparison of the title reaction with SO_2 , H_2O , and $(\text{H}_2\text{O})_2$. As far as abundance of HONO is concerned, it is found in both regions; forested as well as polluted in significant amounts (Kim et al., 2015; Acker et al., 2006; Ren et al., 2010; Zhang et al., 2012; He et al., 2006; Su et al., 2008; Ren et al., 2006; Rondon and Sanhueza, 1989; Zhou et al., 2011; Pawar et al., 2024; Vereecken et al., 2012). Among the two, HONO concentrations are comparatively higher in polluted urban areas, such as megacities. Therefore, we expect HONO to play a more effective role as a sink for Criegee intermediates in such regions. Hence, we have used representative concentrations of HONO and SO_2 in urban areas for the primary comparison. The concentration of water varies greatly in the atmosphere depending upon saturation vapour pressure and relative humidity (RH) (Anglada et al., 2013; Rai and Kumar, 2025). Therefore, in the case of H_2O and $(\text{H}_2\text{O})_2$, we have taken two concentrations; one calculated at 20% RH, and the other calculated at 100% RH. The former serves as lower limits of H_2O and $(\text{H}_2\text{O})_2$ concentrations, whereas the latter serves as the upper limits of H_2O and $(\text{H}_2\text{O})_2$ concentrations. For comparison, we have taken the rate constants reported by Lin et al. (Lin et al., 2016) for H_2O and $(\text{H}_2\text{O})_2$, and by Onel et al. (Onel et al., 2021) for SO_2 . In Figure 3, we have compared the k_{eff} of $\text{CH}_2\text{OO} + \text{HONO}$ with the k_{eff} of $\text{CH}_2\text{OO} + \text{H}_2\text{O}/(\text{H}_2\text{O})_2/\text{SO}_2$ reactions. Figure 3 shows that HONO is a minor sink of simplest Criegee intermediate (CH_2OO) compare to SO_2 , H_2O and $(\text{H}_2\text{O})_2$. In fact, at 100% RH, k_{eff} of $\text{CH}_2\text{OO} + (\text{H}_2\text{O})_2$ is the dominant reaction across the entire temperature range (213–320 K). At 20% RH, k_{eff} for $\text{CH}_2\text{OO} + (\text{H}_2\text{O})_2$ and $\text{CH}_2\text{OO} + \text{H}_2\text{O}$ remain dominant at higher temperatures, specifically within 235–320 K and 260–320 K, respectively. However, at lower temperatures, k_{eff} of $\text{CH}_2\text{OO} + \text{HONO}$ becomes dominant, surpassing both, $\text{CH}_2\text{OO} + (\text{H}_2\text{O})_2$ and $\text{CH}_2\text{OO} + \text{H}_2\text{O}$ in the range of 213–235 K and 213–260

K, respectively. Although $\text{CH}_2\text{OO} + \text{HONO}$ reaction dominates over $\text{CH}_2\text{OO} + (\text{H}_2\text{O})_2$ and $\text{CH}_2\text{OO} + \text{H}_2\text{O}$ at low tempera-
 ture and low humidity, it remains only a minor contributor compared to $\text{CH}_2\text{OO} + \text{SO}_2$ reaction at the same conditions. For
 example, k_{eff} values of $\text{CH}_2\text{OO} + \text{SO}_2$ reaction are ~ 5 times higher than that of $\text{CH}_2\text{OO} + \text{HONO}$ reaction within the whole
 temperature range, indicating that $\text{CH}_2\text{OO} + \text{HONO}$ reaction is never a dominant sink of CH_2OO intermediate.
 Similarly, we have compared our dimethyl substituted Criegee reaction ($(\text{CH}_3)_2\text{COO} + \text{HONO}$) with other known bimolec-
 ular reactions of $(\text{CH}_3)_2\text{COO}$. Here also, we have computed k_{eff} for the comparison (see Figure 4). The rate constants of
 $(\text{CH}_3)_2\text{COO} + \text{SO}_2$ reaction (Smith et al., 2016) is known in the range of 283–303 K, and hence, we have compared its k_{eff}
 in this temperature range with $(\text{CH}_3)_2\text{COO} + \text{HONO}$ reaction. Figure 4 shows that unlike $\text{CH}_2\text{OO} + \text{HONO}$ reaction, here
 k_{eff} of $(\text{CH}_3)_2\text{COO} + \text{HONO}$ is ~ 2 times higher than the same for $(\text{CH}_3)_2\text{COO} + \text{SO}_2$ reaction within 283–303 K. In ad-
 dition, it is worth mentioning that under certain atmospheric conditions, concentration of HONO can be quite high compared
 to SO_2 . For example, during fog events, it is well known that concentration of SO_2 drops significantly (Zhang et al., 2013)
 while concentration of HONO increases (Pawar et al., 2024), making HONO a potentially major bimolecular sink of Criegee
 intermediates in fog-like environments. In addition, as SO_2 mainly comes from human activities, its concentrations are high
 in polluted areas and become quite very low in tropical forests and rural areas. In fact, its concentrations fall below detection
 limits in tropical forest regions (Vereecken et al., 2012). In contrast, although HONO concentration is high in polluted regions
 compared to a clean environment, due to the various *in situ* sources, HONO is present in reasonable amounts even in tropi-
 cal forest areas (Zhang et al., 2012). Therefore, in this region also, HONO is a more effective sink of CI compared to SO_2 .
 Moreover, $\text{CI} + \text{HONO}$ reaction is a hydrogen atom transfer (HAT) process, and hence, the presence of water can effectively
 catalyze this reaction (Buszek et al., 2012; Viegas and Varandas, 2012; Rai and Kumar, 2025). In contrast, the presence of
 water, particularly droplets and aerosols, can act as a sink for SO_2 (Zhang et al., 2013), and hence, in the presence of wa-
 ter, Criegee + SO_2 reaction should be less important compared to $\text{CI} + \text{HONO}$ reaction. After establishing that compared to
 SO_2 , HONO is a more effective sink for $(\text{CH}_3)_2\text{COO}$ under most of the conditions, at last, it is important to compare it with
 $(\text{CH}_3)_2\text{COO} + \text{H}_2\text{O}/(\text{H}_2\text{O})_2$ reactions (Vereecken et al., 2017). It can be seen from Figure 4 that even at 100% RH, k_{eff} of
 $(\text{CH}_3)_2\text{COO} + \text{HONO}$ can dominate over k_{eff} of $(\text{CH}_3)_2\text{COO} + \text{H}_2\text{O}$ and $(\text{CH}_3)_2\text{COO} + (\text{H}_2\text{O})_2$ for a relatively wider range
 of temperatures. For example, the dominant temperature range of $(\text{CH}_3)_2\text{COO} + \text{HONO}$ is, 213–275 K for $(\text{CH}_3)_2\text{COO} +$
 $(\text{H}_2\text{O})_2$ and 213–290 K for $(\text{CH}_3)_2\text{COO} + \text{H}_2\text{O}$. At 20% RH, k_{eff} of $(\text{CH}_3)_2\text{COO} + \text{HONO}$ becomes dominant over k_{eff} of
 both, $(\text{CH}_3)_2\text{COO} + \text{H}_2\text{O}$ and $(\text{CH}_3)_2\text{COO} + (\text{H}_2\text{O})_2$ in almost whole temperature range (213–310 K). For example, at 298 K,
 k_{eff} of $(\text{CH}_3)_2\text{COO} + \text{HONO}$ is $\sim 1.8 \text{ sec}^{-1}$, which is 1.6 times and 2.2 times higher than the same for $(\text{CH}_3)_2\text{COO} + \text{H}_2\text{O}$
 and $(\text{CH}_3)_2\text{COO} + (\text{H}_2\text{O})_2$, respectively. This suggests that the major bimolecular sink of substituted CI can be its reaction
 with HONO in the atmosphere even in the presence of high humidity and SO_2 . At last, it is important to compare the k_{eff} of
 $(\text{CH}_3)_2\text{COO} + \text{HONO}$ reaction with the unimolecular dissociation rate of $(\text{CH}_3)_2\text{COO}$. Figure 4 also contains the unimolecu-
 lar dissociation rate of $(\text{CH}_3)_2\text{COO}$. It is evident from Figure 4 that unimolecular dissociation remains the dominant removal
 path of $(\text{CH}_3)_2\text{COO}$ above 225 K temperature. Only below 225 K temperature, the bimolecular reaction of $(\text{CH}_3)_2\text{COO} +$
 HONO becomes dominant. To conclude, although HONO is a dominant bimolecular sink for $(\text{CH}_3)_2\text{COO}$, it is still primarily
 removed by its unimolecular dissociation, particularly at room temperature. For example, the unimolecular dissociation rate of

266 $(\text{CH}_3)_2\text{COO}$ is $\sim 276 \text{ sec}^{-1}$ at room temperature (Fang et al., 2017) whereas the k_{eff} of $(\text{CH}_3)_2\text{COO} + \text{HONO}$ is only ~ 1.8
 267 sec^{-1} . Interestingly, the unimolecular rate increases rapidly with temperature, while for the bimolecular reaction $(\text{CH}_3)_2\text{COO}$
 268 $+ \text{HONO}$, k_{eff} decreases only slightly. As a result, at lower temperatures, k_{eff} may become comparable to the unimolecular
 269 dissociation rate of $(\text{CH}_3)_2\text{COO}$. For example, at 213 K, k_{eff} and the unimolecular rate constants are 3.80 sec^{-1} and 1.82
 270 sec^{-1} , respectively. A comparison between k_{eff} and the unimolecular dissociation rate constant of $(\text{CH}_3)_2\text{COO}$ within 213–
 271 320 K is provided in Table S6 of the ESI. It is evident from Table S6 that under conditions of high HONO concentration and
 272 low temperature, the bimolecular reaction of $(\text{CH}_3)_2\text{COO}$ with HONO can compete with its unimolecular dissociation.
 273 Finally, it is important to assess the extent to which the title reaction can contribute in resolving the puzzle of mismatch be-
 274 tween measured and modelled $\text{OH}^\bullet/\text{HO}_2^\bullet$ concentrations. It is important to mention that during daytime, HONO undergoes
 275 rapid photolysis; therefore, its concentration is higher in the absence of light, e.g. at night, indoors, in winter, etc. For example,
 276 the photolysis rate of HONO is known to be $\sim 10^{-3} \text{ sec}^{-1}$, which is several orders of magnitude higher than the effective rate
 277 constant of its reaction with Criegee intermediates ($\sim 10^{-7} - 10^{-6} \text{ sec}^{-1}$, computed using maximum Criegee concentration
 278 of $\sim 10^5 \text{ molecule cm}^{-3}$) (Shabin et al., 2023). Therefore, during the peak of daytime, title reaction does not contribute much
 279 to $\text{OH}^\bullet$ production; rather, it can play a key role in nocturnal atmospheric chemistry, specifically at times when both, concen-
 280 trations of HONO and CI are high, and, at the same time, the presence of light is minimal. To understand the efficiency of the
 281 title reaction in affecting $\text{OH}^\bullet$ concentration in a nocturnal environment, we can compare it with $\text{NO}_3^\bullet + \text{HO}_2^\bullet$ reaction, which
 282 is a well-known source of $\text{OH}^\bullet$ at nighttime. The rate constants for $\text{CH}_2\text{OO} + \text{HONO}$ reaction are ~ 2 times higher compared
 283 to $\text{NO}_3^\bullet + \text{HO}_2^\bullet$. For example, at 298 K, the rate value for $\text{CH}_2\text{OO} + \text{HONO}$ is $\sim 7.21 \times 10^{-12} \text{ cm}^3 \text{ molecule}^{-1} \text{ sec}^{-1}$, which is
 284 almost double compared to the rate value (Rai and Kumar, 2024) for $\text{NO}_3^\bullet + \text{HO}_2^\bullet$, i.e., $\sim 3.36 \times 10^{-12} \text{ cm}^3 \text{ molecule}^{-1} \text{ sec}^{-1}$.
 285 In the atmosphere, average concentration of both $\text{NO}_3^\bullet$ and $\text{HO}_2^\bullet$ are $\sim 10^8 \text{ molecule cm}^{-3}$ (Bottorff et al., 2023; Brown and
 286 Stutz, 2012), thus combined concentration turns out to be $\sim 10^{16} \text{ molecule}^2 \text{ cm}^{-6}$. Similarly, the combined concentration will
 287 be $\sim 10^{15} \text{ molecule}^2 \text{ cm}^{-6}$ for $\text{CH}_2\text{OO} + \text{HONO}$ under high concentrations of CI ($\sim 10^5 \text{ molecule cm}^{-3}$) (Khan et al., 2018)
 288 and HONO ($\sim 10^{10} \text{ molecule cm}^{-3}$) (Pawar et al., 2024). It suggests that $\text{CH}_2\text{OO} + \text{HONO}$ reaction may be somewhat slower
 289 in producing $\text{OH}^\bullet$. However, since the rate of $(\text{CH}_3)_2\text{COO} + \text{HONO}$ reaction is one order of magnitude higher compared to
 290 $\text{NO}_3^\bullet + \text{HO}_2^\bullet$, we believe both $\text{NO}_3^\bullet + \text{HO}_2^\bullet$ and title reactions should be of similar importance as far as the production of night-
 291 time $\text{OH}^\bullet$ is concerned. In other words, title reaction has the potential to serve as a significant contributor to $\text{OH}^\bullet$ production
 292 in nighttime atmospheric chemistry.
 293 Another factor worth noting is, besides $\text{OH}^\bullet$, the title reaction produces $\text{HCHO}/(\text{CH}_3)_2\text{CO}$, and $\text{NO}_2^\bullet$ as products. It is well
 294 known that both $\text{HCHO}/(\text{CH}_3)_2\text{CO}$ (Gao et al., 2024; Long et al., 2022; Hermans et al., 2004) and $\text{NO}_2^\bullet$ (Christensen et al.,
 295 2004) can act as sinks for HO_2 radicals (corresponding reactions are listed in the box below). It suggests that title reaction has
 296 the potential for recycling of $\text{HO}_2^\bullet \leftrightarrow \text{OH}^\bullet$ process. To illustrate the ability of title reaction in recycling $\text{HO}_2^\bullet \leftrightarrow \text{OH}^\bullet$ process,
 297 we have developed a kinetic model consisting of the following reactions (see ESI for the details):



298

299 This model requires two key components: first, the rate coefficients of the relevant reactions, which have been taken from
300 the recommended literature values (Gao et al., 2024; Hermans et al., 2004; Long et al., 2022; Christensen et al., 2004), and
301 second, a list of realistic initial concentrations of the reactive species involved in $\text{HO}_2^\bullet \leftrightarrow \text{OH}^\bullet$ recycling process (Table S5
302 of the ESI). We first tracked the change in concentration of $\text{OH}^\bullet$ and $\text{HO}_2^\bullet$ using the first kinetic model consisting of CH_2OO
303 + HONO reaction, followed by second model consisting of $(\text{CH}_3)_2\text{COO} + \text{HONO}$ reaction. Initial concentrations of relevant
304 species (HCHO, HONO, $(\text{CH}_3)_2\text{CO}$, and $\text{HO}_2^\bullet$) are chosen based on literature values representing polluted urban conditions
305 (Vereecken et al., 2012; Pawar et al., 2024). Although the average concentration of $\text{OH}^\bullet$ can vary within $\sim 10^4$ – 10^6 molecules
306 cm^{-3} in the atmosphere, we have used a modelled value of it in the present work. In $\text{CH}_2\text{OO} + \text{HONO}$ reaction model,
307 the initial $\text{OH}^\bullet$ concentration was set to $\sim 10^4$ molecules cm^{-3} , while in $(\text{CH}_3)_2\text{COO} + \text{HONO}$ model, it was set to $\sim 10^5$
308 molecules cm^{-3} . This difference was chosen based on how much OH each reaction is expected to produce when no *in situ*
309 reactions are taking place from the byproducts of the title reaction. Since $(\text{CH}_3)_2\text{COO} + \text{HONO}$ reaction can generate more
310 OH, starting with a higher initial concentration helps one observe a noticeable change in $\text{OH}^\bullet$ levels during the simulation.
311 This makes it easier to observe and compare the effect of $\text{OH}^\bullet$ production between the two reactions. It is important to mention
312 that the maximum concentration of $\text{OH}^\bullet$ can be taken as $\sim 10^5$ molecules cm^{-3} in the kinetic model. This is because the
313 production of $\text{OH}^\bullet$ is limited by the available concentration of CI which can be as high as $\sim 10^5$ molecules cm^{-3} . Therefore,
314 taking $\text{OH}^\bullet$ concentration more than $\sim 10^5$ molecules cm^{-3} would produce no effect on the concentration of $\text{OH}^\bullet$. This also
315 reveals the fact that the title reaction is capable of producing $\text{OH}^\bullet$ in regions where the concentration of $\text{OH}^\bullet$ is already low.
316 Similarly, the concentration of NO_2 can vary within $\sim 10^{10}$ – 10^{12} molecules cm^{-3} in polluted urban regions. However, in the
317 present model, we have kept it at $\sim 10^{10}$ molecules cm^{-3} in order to observe a clear numerical change in the values of $\text{HO}_2^\bullet$.
318 Taking a high concentration of NO_2 ($\sim 10^{12}$ molecules cm^{-3}) would drastically consume $\text{HO}_2^\bullet$, and a gradual change would
319 not be observed.

320 We have divided the simulation results into two parts; first we will discuss $\text{CH}_2\text{OO} + \text{HONO}$ reaction followed by $(\text{CH}_3)_2\text{COO}$
321 + HONO. The model results have been shown in Figure 5. It is evident from Figure 5 that $\text{CH}_2\text{OO} + \text{HONO}$ reaction increases
322 $\text{OH}^\bullet$ concentration while simultaneously reducing $\text{HO}_2^\bullet$ concentration. Quantitatively, this reaction increases $\text{OH}^\bullet$ production
323 by five times its initial value while decreasing $\text{HO}_2^\bullet$ production by more than one order of magnitude. Furthermore, when
324 we consider dimethyl-substituted Criegee intermediate reaction ($(\text{CH}_3)_2\text{COO} + \text{HONO}$), $\text{OH}^\bullet$ production has been found to
325 increase by only a factor of two compared to its initial concentration, while $\text{HO}_2^\bullet$ production again decreases by the same one
326 order of magnitude (Figure 5). The difference in $\text{OH}^\bullet$ production can be attributed to the fact that, in case of $(\text{CH}_3)_2\text{COO} +$

327 HONO, the initial OH• concentration was taken to be $\sim 10^5$ molecules cm^{-3} compared to $\sim 10^4$ molecules cm^{-3} in case of
328 $\text{CH}_2\text{OO} + \text{HONO}$. This further strengthens the fact that the effect of title reaction on OH• production will be more pronounced
329 in the conditions where OH• concentration is lower in the atmosphere, e.g., at night. The overall simulation results suggest that
330 incorporating title reaction into atmospheric models can improve their accuracy in predicting OH• and HO_2 concentrations.
331 It is important to note that the kinetics model used in the present work is preliminary. However, a more realistic impact of the
332 title reaction on the budget of both OH• and HO_2 , requires a more complete modeling. In order to do so, one needs accurate
333 estimation of the rate constants for the reaction of HONO with various important Criegee intermediates. For bigger Criegee
334 intermediates, computation will be more costly and require a separate study. In addition, being a HAT reaction, the effect of
335 humidity on the title reaction is also important to build a complete model.

336 5 Conclusions

337 In this work, we have studied the energetics and kinetics of bimolecular reaction of simple and dimethyl-substituted Criegee
338 with HONO using high-level electronic structure theory and chemical kinetics. Our quantum chemical calculations suggest that
339 both of the reactions are barrierless and kinetic calculations reveal that reaction of substituted Criegee with HONO is ~ 2.6 – 3.6
340 times faster than simple Criegee + HONO reaction. By comparing it with other known sinks of CI, we have shown that HONO
341 can serve as a major bimolecular sink for bigger Criegee intermediate $((\text{CH}_3)_2\text{COO})$ and minor contributor at low humidity and
342 low temperature for simple CH_2OO . In addition, we have also shown that title reaction can be an important source of OH• in
343 nocturnal atmosphere. In addition, the products of CI + HONO reaction can be a sink for HO_2 radicals, and hence this reaction
344 is capable of $\text{HO}_2 \leftrightarrow \text{OH}^\bullet$ recycling. Consequently, this reaction can be key in fulfilling the gap between the observed OH
345 radicals and modelled values. Although in urban areas, HONO can be the dominant sink of certain CIs, it is important to notice
346 that larger Criegee intermediates predominantly originate from biogenic volatile organic compounds (BVOCs). On the other
347 hand, HONO concentrations in forested regions are also found to be moderate ($\sim 10^8$ to 10^{10} molecules cm^{-3}). Therefore, we
348 believe a separate study is required to understand the fate of larger Criegee intermediates in the presence of HONO. At last, we
349 look forward to the experimental verification of our results.

350 *Author contributions.* VJA: Conducted the investigation, Writing—original draft, Formal analysis, curated the data. PKR: Contributed to par-
351 tial formal analysis, writing, reviewing, and editing the manuscript. PK: Provided supervision, resources, and methodology; conceptualized
352 the study; acquired funding; and contributed to the review and editing of the manuscript.

353 *Competing interests.* The authors declare that they have no conflict of interest.

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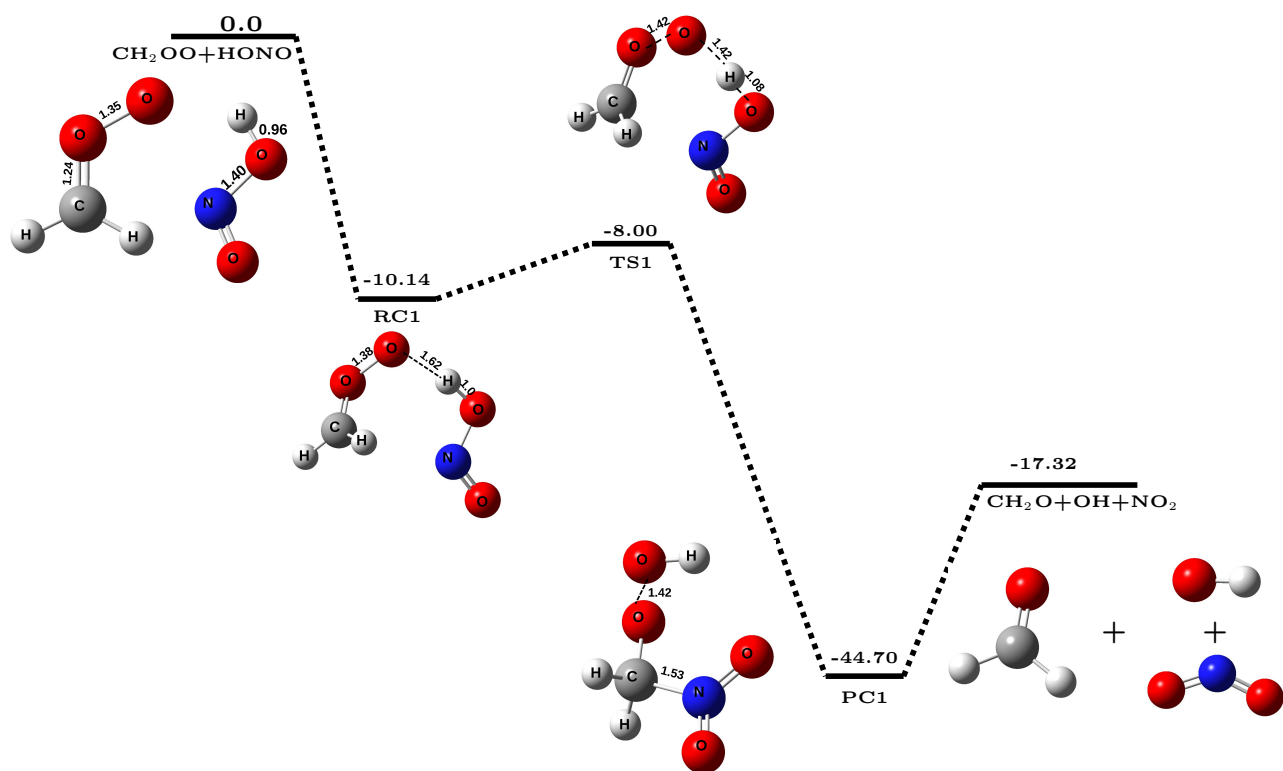


Figure 1. The potential energy surface for CH₂OO + HONO reaction (in kcal mol⁻¹) obtained at CCSD(T)/CBS//M06-2X/aug-cc-pVTZ level of theory along with optimized geometries of species involved in the reaction.

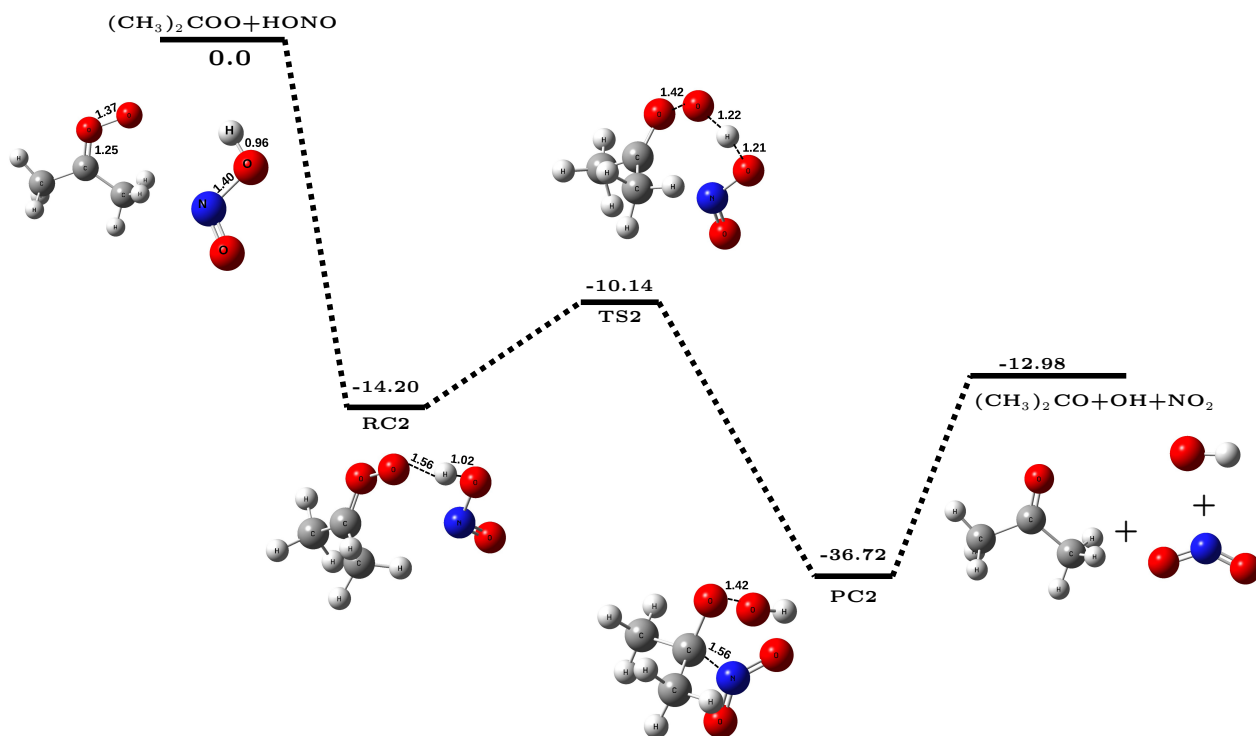


Figure 2. The potential energy surface for $(\text{CH}_3)_2\text{COO} + \text{HONO}$ reaction (in kcal mol⁻¹) obtained at CCSD(T)/CBS//M06-2X/aug-cc-pVTZ level of theory along with optimized geometries of species involved in the reaction.

Table 1. Bimolecular rate constants (k_{bi} , in $\text{cm}^3 \text{ molecule}^{-1} \text{ sec}^{-1}$) for $\text{CH}_2\text{OO}/(\text{CH}_3)_2\text{COO} + \text{HONO}$ reaction within the temperature range of 213–320 K.

T (K)	$k_{bi}^{\text{CH}_2\text{OO}}$	$k_{bi}^{(\text{CH}_3)_2\text{COO}}$
213	1.17×10^{-11}	4.28×10^{-11}
216	1.15×10^{-11}	4.18×10^{-11}
219	1.13×10^{-11}	4.09×10^{-11}
224	1.11×10^{-11}	3.94×10^{-11}
235	1.04×10^{-11}	3.61×10^{-11}
250	9.58×10^{-12}	3.18×10^{-11}
259	9.10×10^{-12}	2.94×10^{-11}
265	8.79×10^{-12}	2.78×10^{-11}
278	8.14×10^{-12}	2.47×10^{-11}
280	8.04×10^{-12}	2.42×10^{-11}
290	7.57×10^{-12}	2.20×10^{-11}
298	7.21×10^{-12}	2.03×10^{-11}
300	7.13×10^{-12}	1.99×10^{-11}
310	6.70×10^{-12}	1.80×10^{-11}
320	6.30×10^{-12}	1.63×10^{-11}

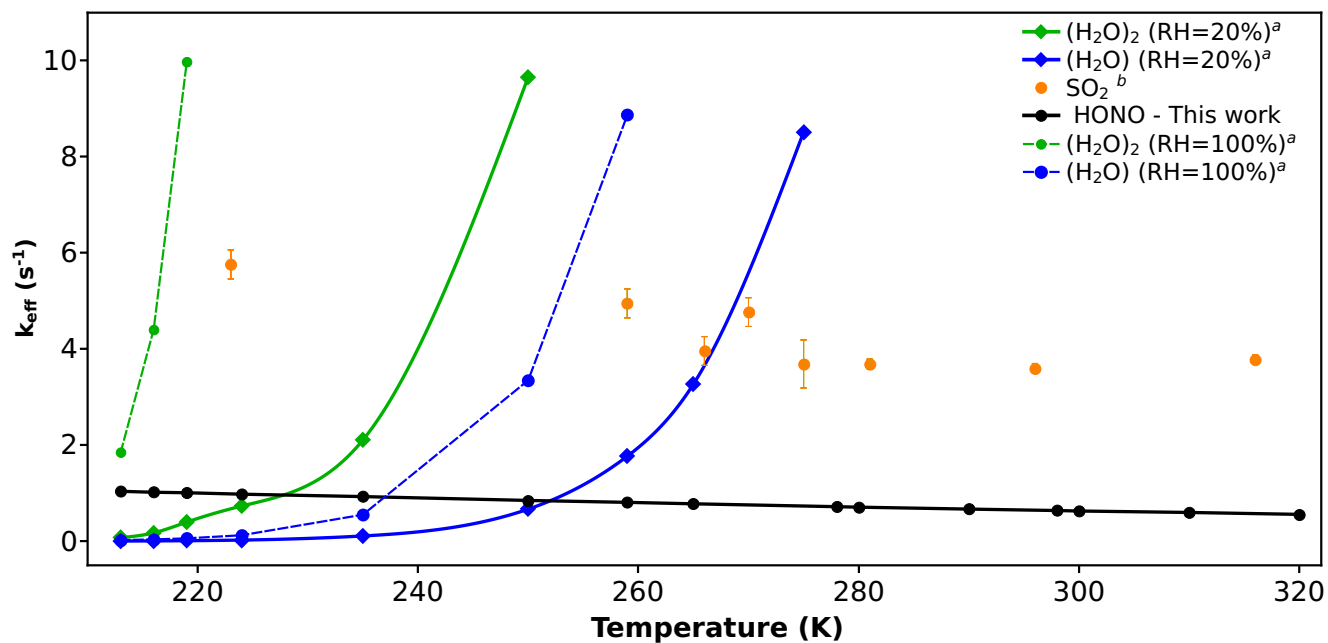


Figure 3. Effective rate constant comparison (k_{eff} , in sec^{-1}) of CH_2OO + HONO with the k_{eff} of previously known sinks of CH_2OO .

a. Values are taken from reference (Lin et al., 2016)

b. Values are taken from reference (Onel et al., 2021)

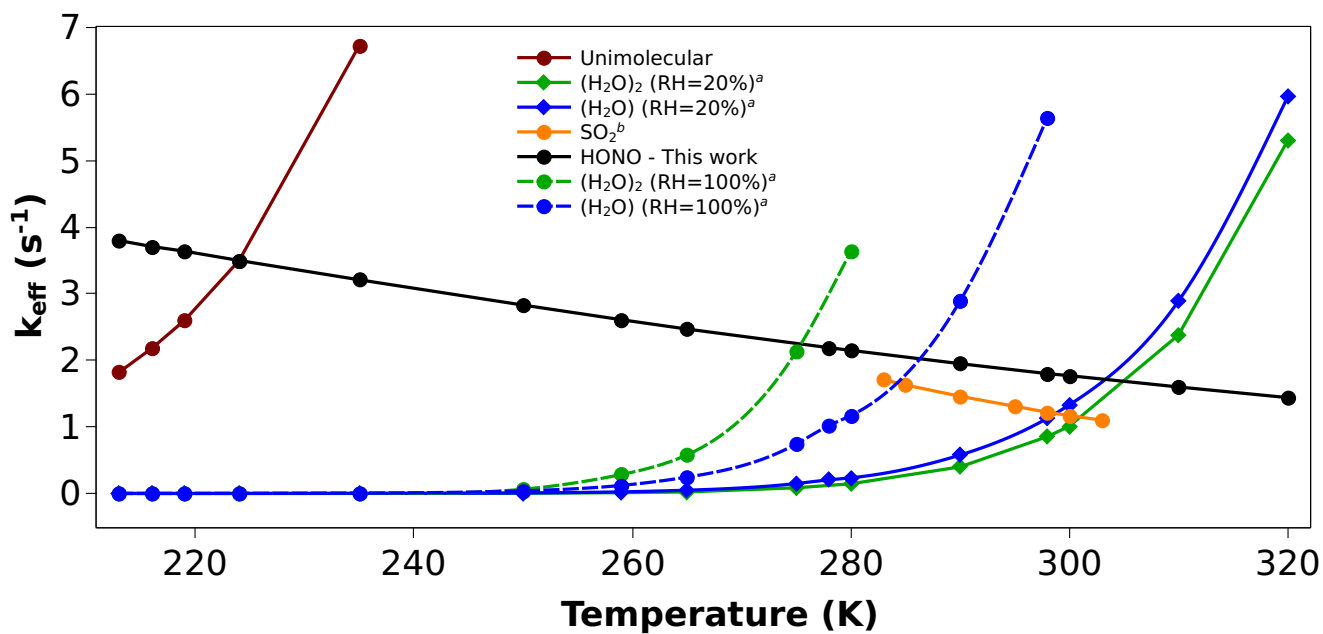


Figure 4. Effective rate constant comparison (k_{eff} , in sec^{-1}) of $(\text{CH}_3)_2\text{COO} + \text{HONO}$ with the k_{eff} of previously known sinks of $(\text{CH}_3)_2\text{COO}$.

a. Values are taken from reference (Vereecken et al., 2017)

b. Values are taken from reference (Smith et al., 2016)

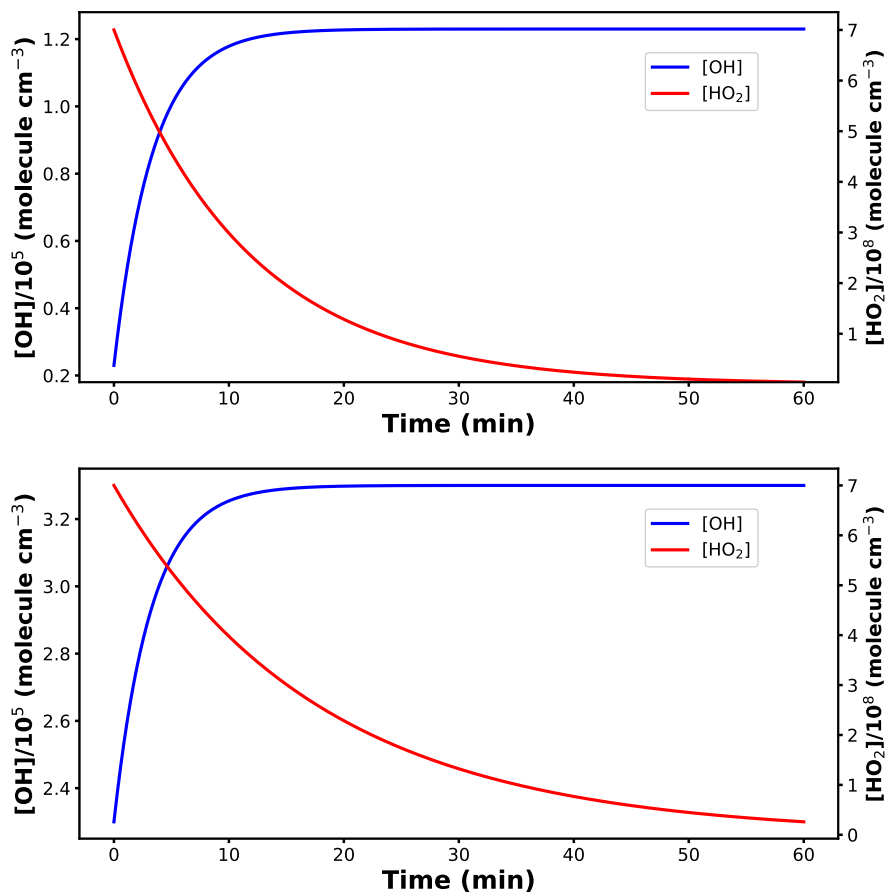


Figure 5. Top panel: Concentration profiles of $\text{HO}_2^\bullet$ and $\text{OH}^\bullet$ using $\text{CH}_2\text{OO} + \text{HONO}$ reaction into the model. Bottom panel: Concentration profiles of $\text{HO}_2^\bullet$ and $\text{OH}^\bullet$ using $(\text{CH}_3)_2\text{COO} + \text{HONO}$ reaction into the model.