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Autoxidation of terpenes, a common pathway in tropospheric and low temperature combustion conditions: the case of limonene and α-pinene.

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Abstract.

The oxidation of monoterpenes under atmospheric conditions has been the subject of numerous studies. They were motivated by the formation of oxidized organic molecules (OOM) which, due to their low vapor pressure, contribute to the formation of secondary organic aerosols (SOA). Among the different reaction mechanisms proposed for the formation of these oxidized chemical compounds, it appears that the autoxidation mechanism, involving successive events of H-migration and O_2 addition, common to both low-temperature combustion and atmospheric conditions, is leading to the formation of highly oxidized molecules (HOM). In atmospheric chemistry, the importance of autoxidation compared to other oxidation pathways has been the topic of numerous studies. Conversely, in combustion, autoxidation under cool flame conditions is the main oxidation process commonly taken into account. An analysis of oxidation products detected in both conditions was performed, using the present combustion data and literature data from tropospheric oxidation studies, to investigate possible similarities in terms of observed chemical formulae of products. To carry out this study, we chose two terpenes, α-pinene and limonene ($C_{10}H_{16}$), among the most abundant biogenic components in the atmosphere, and considered in many previous studies. Also, these two isomers were selected for the diversity of their reaction sites (exo- and endo- carbon-carbon double bonds). We built an experimental database consisting of literature atmospheric oxidation data and presently obtained combustion data for the oxidation of the two selected terpenes. In order to probe the effects of the type of ionization used in mass spectrometry analyses on the detection of oxidation products, we used heated electrospray ionization (HESI) and atmospheric pressure chemical ionization (APCI), in positive and negative modes. The oxidation of limonene-oxygen-nitrogen and α-pinene-oxygen-nitrogen mixtures was performed using a jet-stirred reactor at elevated temperature (590 K), a residence time of 2 s, and atmospheric pressure. Samples of the reacting mixtures were collected in acetonitrile and analyzed by high-resolution mass spectrometry (Orbitrap Q-Exactive) after direct injection and soft ionization, i.e. (+/–) HESI and (+/–) APCI. This work shows a surprisingly similar set of chemical formulae of products, including oligomers, formed in cool flames and under simulated atmospheric conditions. Data analysis showed that a non-negligible subset of chemical formulae is common to all experiments independently of experimental parameters. Finally, this study indicates that more than 40% of the detected chemical formulae in this full dataset can be ascribed to an autoxidation mechanism.

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1 Introduction

The links between atmospheric and combustion chemistry have often been studied from the point of view of tropospheric reactions of combustion effluents or pollutants, e.g., oxidation of volatile organic compounds, nitrogen oxides reactions, sulfur chemistry (Barsanti et al., 2017;Shrivastava et al., 2017;Zhao et al., 2018;Bianchi et al., 2019). Climate change and the increase of large wildfire events have profoundly modified the relationship between atmospheric chemistry and combustion at large. When studying the oxidation of chemicals and the formation of SOA in the atmosphere, it becomes necessary to determine the contribution of different oxidation pathways pertaining to atmospheric chemistry, combustion chemistry, or both.

In low-temperature combustion (cool flame) the formation of oxidized organic molecules (OOM) is mainly attributed to autoxidation reactions (Belhadj et al., 2021;Benoit et al., 2021), whereas in atmospheric chemistry, it is only relatively recently that this pathway has been considered (Vereecken et al., 2007;Crounse et al., 2013;Jokinen et al., 2014a;Berndt et al., 2015;Jokinen et al., 2015a;Berndt et al., 2016;Iyer et al., 2021). Also, it has been identified that highly oxygenated molecules (HOMs), a source of secondary organic aerosols (SOA), can result from autoxidation processes (Wang et al., 2021;Tomaz et al., 2021;Bianchi et al., 2019). Modeling studies complemented by laboratory experiments showed that autoxidation mechanisms proceed simultaneously on different $RO_2^{\cdot}$ radicals and leads to, through isomerization and addition of O_2, the production of a wide range of oxidized compounds in a few hundredths of a second (Jokinen et al., 2014a;Berndt et al., 2016;Bianchi et al., 2019). Autoxidation is based on an H-shift and oxygen addition which starts with the initial production of $RO_2^{\cdot}$ radicals. This mechanism can repeat itself several times and lead to recurrent oxygen additions to form HOMs: R+ O_2 ⇄ ROO˙ (first O_2-addition); ROO˙ ⇄˙QOOH (H-shift); ˙QOOH +O_2 ⇄ ˙OOQOOH (second O_2-addition); ˙OOQOOH ⇄ HOOQ˙˙OOH (H-shift); HOOQ˙˙OOH +O_2 ⇄ $(HOO)_2Q$˙OO˙ (third O_2-addition); $(HOO)_2Q$˙OO˙ ⇄ $(HOO)_2Q$˙˙˙OOH (H-shift); $(HOO)_2Q$˙˙˙OOH +O_2 ⇄ $(HOO)_3Q$˙˙ OO˙ (fourth O_2-addition) etc. Recent works have shown that, under certain atmospheric conditions, this autoxidation mechanism could be competitive with other reaction pathways involving $RO_2^{\cdot}$ radicals (Bianchi et al., 2019), e.g., the carbonyl channel (ROO˙ → $R_{-H}O$ + OH), the hydroperoxide channel (ROO˙ + HOO˙ → ROOH + O_2 and RO˙ + ˙OH + O_2), disproportionation reactions (ROO˙ + R'OO˙ → RO˙ + R'O˙ + O_2 and $R_{-H}O$ + R'OH + O_2), accretion reactions (ROO˙ + R'OO˙ → ROOR' + O_2). A study published in 2021 showed that the oxidation of alkanes follows this autoxidation mechanism under both atmospheric and combustion conditions (Wang et al., 2021). Also, that work confirmed that internal H-shifts in autoxidation can be promoted by the presence of functional groups, as predicted earlier (Otkjær et al., 2018) for $RO_2^{\cdot}$ radicals containing OOH, OH, OCH_3, CH_3, C=O, or C=C groups. To further assess the importance of these pathways, available data must be compared along with their experimental specificities. In laboratory studies under simulated atmospheric conditions, oxidation occurs at near-ambient temperatures (250-300 K), at atmospheric pressure, in the presence of ozone and/or $OH^{\cdot}$ radicals, and with low initial terpene concentrations. In combustion, the $OH^{\cdot}$ radical, temperature, and pressure are driving autoxidation. Initial reactant concentrations are generally higher compared to atmospheric conditions, so as to compensate for the absence of ozone and get oxidation to proceed, since terpenes, as other hydrocarbons, react very slowly with O_2. Rising temperature increases isomerization rates and favors autoxidation, at the expense of other possible reactions of $RO_2^{\cdot}$ radicals. In atmospheric chemistry, at near room temperature, autoxidation can be initiated via two reaction mechanisms: reactions with ozone or with the $OH^{\cdot}$ radical. Suppression of one of these pathways by scavengers

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generally changes the amount of products formed (sometimes a drastic decrease >90% was observed (Kenseth et al., 2018;Meusinger et al., 2017;Pospisilova et al., 2020)), but does not affect the diversity of observed chemical formulae (Zhao et al., 2018;Pospisilova et al., 2020). It has been reported earlier that a temperature rise from 250 to 273K does not affect the distribution of HOMs (Quéléver et al., 2019) whereas Trostl et al. suggested that the distribution of HOMs is affected by temperature, α-pinene or particle concentration (Tröstl et al., 2016). Similarly, the experiments of Huang et al. performed at different temperatures (223 K and 296 K) and precursor concentration (α-pinene 0.714 and 2.2 ppm) suggested that the physicochemical properties, such as the composition of the oligomers, can be affected by a variation of temperature (Huang et al., 2018). Both in combustion and atmospheric chemistry, autoxidation can yield highly oxygenated molecules (HOMs), e.g., compounds containing more than 7 oxygen atoms (Benoit et al., 2021;Bianchi et al., 2019). The term 'HOM' is generally associated with atmospheric chemistry (Bianchi et al., 2019), but this nomenclature does not specify the chemical properties of a compound. In other words, in combustion we can also observe highly oxidized chemical compounds similar to those relevant to atmospheric chemistry. The broad range of chemical molecules formed and the impact of the experimental conditions on their character remain a subject for atmospheric chemistry as well as combustion chemistry studies. Moreover, whatever the mechanism of aerosol formation, i.e., oligomerization, addition, or accretion, their composition will be linked to that of the initial radical pool (Tomaz et al., 2021).

In low-temperature combustion, when the temperature is increased, autoxidation rate goes through a maximum between 500 and 670 K, depending on the nature of the fuel (Belhadj et al., 2020;Belhadj et al., 2021), and the rate of formation of HOM also increases (Bianchi et al., 2019). Therefore, temperature has a measurable effect on the amount of HOMs formed (Wang et al., 2021). In low-temperature combustion chemistry as in atmospheric chemistry, the oxidation of a chemical compound leads to the formation of several thousands of chemical products which result from successive additions of oxygen, isomerization, accretion, fragmentation, and oligomerization (Benoit et al., 2021). The exhaustive analysis of chemical species remains, in the current state of instrumental limitations, impossible. This would consist in analyzing several thousands of molecules in MS^2 mode using separative techniques such as ultra-high pressure liquid chromatography (UHPLC) or ion mobility spectrometry (IMS) (Krechmer et al., 2016;Kristensen et al., 2016). Nevertheless, it is possible to classify these molecular species, considering only $C_xH_yO_z$ compounds, according to various criteria accessible via graphic tools representation such as van Krevelen diagrams, double bond equivalent number (DBE), and average carbon oxidation state (OSc) versus the number of carbon atoms (Kourtchev et al., 2015;Nozière et al., 2015). Such postprocessing of large datasets has the advantage of immediately highlighting families of compounds or physicochemical properties such as the condensation of molecules (vapor pressure), the large variety of oxygenated products ($C_xH_yO_{1\text{-}15}$ in the present experiments) and the formation of oligomers (Kroll et al., 2011;Xie et al., 2020).

In addition to the recent studies focusing on the first steps of autoxidation, a more global approach, based on the comparison of possible chemical transformations related to autoxidation in low temperature combustion and atmospheric chemistry, is needed for evaluating the importance of autoxidation under tropospheric and low-temperature combustion conditions. In order to study the effects of ozonolysis and combustion on the diversity of chemical molecules formed by autoxidation, we have selected α-pinene and limonene, two terpene isomers among the most abundant in the troposphere. Limonene has a single ring structure and two double bonds, one of which is exocyclic. α-Pinene has a bicyclic structure and a single endo-cyclic double bond. These two isomers with their distinctive characters are good candidates for studying autoxidation versus initial chemical structure and

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temperature. For α-pinene, in addition to the reactivity of its endo-cyclic double bond, products of ring opening of the cyclobutyl group have been detected, which could explain the diversity of observed oxidation products (Kurtén et al., 2015;Iyer et al., 2021). This large pool of products is increased in the case of limonene by the presence of two double bonds (Hammes et al., 2019;Jokinen et al., 2015a). Nevertheless, the diversity of oxidation products can be compensated by similarities in terms of reaction mechanisms and intermediates formed through autoxidation (Savee et al., 2015).

In the present work, which is a prolongation of that published earlier for the oxidation of limonene alone (Benoit et al., 2021), we oxidized α-pinene and limonene in a jet-stirred reactor at atmospheric pressure, excess of oxygen, and elevated temperature. Then, we characterized the impact of using different ionization techniques (HESI and APCI) in positive and negative modes on the pool of detected chemical formulae. The particularities of each ionization mode were analyzed to identify the most suitable ionization technique for exploring the formation of autoxidation products under low temperature combustion. Chemical formulae detected here and in atmospheric chemistry studies were compiled and tentatively used to evaluate the importance of autoxidation under both conditions.

2 Experiments

2.1 Oxidation experiments

The present experiments were carried out in a fused silica jet-stirred reactor (JSR) setup presented earlier (Dagaut et al., 1986;Dagaut et al., 1988) and used in previous studies (Dagaut et al., 1987;Benoit et al., 2021;Belhadj et al., 2021). The two isomers α-pinene and limonene were studied separately. As in earlier works (Benoit et al., 2021;Belhadj et al., 2021), α-pinene (+), 98% pure from Aldrich and limonene (R)-(+), >97% pure from Sigma, were pumped by an HPLC pump (Shimadzu LC10 AD VP) with an online degasser (Shimadzu DGU-20 A3) and sent to a vaporizer assembly where it was diluted by a nitrogen flow. Each terpene isomer and oxygen, both diluted by N_2, were sent separately to a 42 mL JSR to avoid oxidation before reaching 4 injectors (nozzles of 1 mm I.D.) providing stirring. The flow rates of nitrogen and oxygen were controlled by mass flow meters. Good thermal homogeneity along the vertical axis of the JSR was recorded (gradients of < 1 K/cm) by thermocouple measurements (0.1 mm Pt-Pt/Rh-10% wires located inside a thin-wall silica tube). In order to observe the oxidation of these isomers, which are not prone to strong self-ignition, the oxidation of 1% of these chemical compounds ($C_{10}H_{16}$) under lean fuel conditions (equivalence ratio 0.25, 56% O_2, 43% N_2), experiments were carried out at 590 K, atmospheric pressure, and a residence time of 2 s. Under these conditions, the oxidation of the two isomers is initiated by slow H-atom abstraction by molecular oxygen. The fuel radicals react rapidly with O_2 to form peroxy radicals which undergo further oxidation, characteristic of autoxidation. The absence of ozone, and no need for the addition of a scavenger, allow probing reaction mechanisms and observing chemical species potentially specific to autoxidation initiated by OH radicals. A 2 mm I.D. probe was used to collect samples. To measure low-temperature oxidation products ranging from early oxidation steps to highly oxidized molecules, the sonic probe samples were bubbled in cooled acetonitrile (UHPLC grade ≥99.9, T= 0°C, 250 mL) for 90 min. The resulting solution was stored in a freezer at -15°C.

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2.2 Chemical analyses

Analyses of samples collected in acetonitrile were performed by direct sample instillation (rate: 3µL/min and recorded for 1 min for data averaging) in the ionization chamber of a high-resolution mass spectrometer (Thermo Scientific Orbitrap® Q-Exactive, mass resolution 140,000 and mass accuracy <0.5 ppm RMS). Both heated electrospray ionization (HESI) and atmospheric chemical ionization (APCI) were used in positive and negative modes for the ionization of products. HESI settings were: spray voltage 3.8 kV, T vaporizer of 150°C, T capillary 200°C, sheath gas flow of 8 arbitrary units (a.u.), auxiliary gas flow of 1 a.u., sweep gas flow of 0 a.u.. In APCI, settings were: spray voltage 3.8 kV, vaporizer temperature of 150°C, capillary temperature of 200°C, sheath gas flow of 8 a.u., auxiliary gas flow of 1 a.u., sweep gas flow of 0 a.u., corona current of 3µA. In order to avoid transmission and detection effects of ions depending on their mass inside the C-Trap (Hecht et al., 2019), acquisitions with three mass ranges were performed (m/z 50-750; m/z 150-750; m/z 300-750). The upper limit of m/z 750 was chosen because of the absence of signal beyond this value. We verified that no significant oxidation occurred in the HESI and APCI ion sources by injecting a limonene-ACN mixture. The optimization of the Orbitrap ionization parameters in HESI and APCI did not show any clustering phenomenon for these two isomers. The parameters evaluated were: injection source - capillary distance, vaporization and capillary temperatures, applied difference of potential, injected volume, flow rate of nitrogen in the ionization source. Positive and negative HESI mass calibrations were performed using Pierce™ calibration mixtures (Thermo Scientific). Chemical compounds with relative intensity less than 1 ppm to the highest mass peak in the mass spectrum were not considered. Nevertheless, it should be considered that some of the molecules presented in this study could result from our experimental conditions (continuous flow reactor, reagent concentration, temperature, reaction time) and to some extent from our acquisition conditions, different from those of the previous studies (Deng et al., 2021;Quéléver et al., 2019;Meusinger et al., 2017;Krechmer et al., 2016;Tomaz et al., 2021;Fang et al., 2017;Witkowski and Gierczak, 2017;Jokinen et al., 2015b;Nørgaard et al., 2013;Bateman et al., 2009;Walser et al., 2008;Warscheid and Hoffmann, 2001;Hammes et al., 2019;Kundu et al., 2012). Indeed, the use of a continuous flow reactor operating at elevated temperature, as well as a high initial concentration of reagents can induce the formation of combustion-specific products, which does not exclude their possible formation under atmospheric conditions.

3 Data Processing

High resolution mass spectrometry (HR-MS) generates a large amount of data that is difficult to fully analyze by sequential methods. When the study requires the processing of several thousands of molecules, the use of statistical tools and graphical representation means becomes necessary. In this study, we have chosen to use the van Krevelen diagram (Van Krevelen, 1950) by adding an additional dimension, the double bond equivalent (DBE). The DBE number represents the sum of unsaturation and rings present in a chemical compound (Melendez-Perez et al., 2016).

$$DBE = 1 + C - H/2 - O$$

This number is independent of the number of oxygen atoms, but changes with the number of hydrogen atoms. Decimal values of this number, which correspond to an odd number of hydrogen atoms, were not considered in this study. Then, duplications of chemical formulae in the O/C vs. H/C space are eliminated. The oxidation state

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of carbon (OSc) provides a measure of the degree of oxidation of chemical compounds (alcohols, aldehydes, carboxylic acids, esters, ethers and ketones, but not peroxides) (Kroll et al., 2011). This provides a framework for describing the chemistry of organic species. It is defined by the following equation:

$$OSc \approx 2\ O/C - H/C$$

4 Results and discussion

The oxidation of the two isomers, α-pinene and limonene ($C_{10}H_{16}$), was studied at 590 K, under atmospheric pressure, with a residence time of 2 s and a fuel concentration of 1%. Under these conditions, the formation of peroxides by autoxidation at low temperature should be optimal (Belhadj et al., 2021), even if the conversion of the fuels remains moderate.

4.1 Characterization of ionization sources

First, we have studied the impact of APCI and HESI sources, in positive and negative modes, on the chemical formulae detected. The HESI and APCI sources in positive and negative mode were used and their operating parameters were varied, i.e., temperature, gas flow and accelerating voltage (see Section 2). For each polarity, only ions composed of carbon, hydrogen (even numbers) and oxygen were considered. Molecular duplicates inherent to mass range overlaps were excluded. Chemical formulae with relative intensity less than 1 ppm with respect to the highest mass peak of the mass spectrum were not considered. By following these rules, we obtained a different number of ions depending on the ionization source and the polarity used. Table 1 shows the number of ions according to the experimental conditions and the discrimination rules.

Table 1. Number of ions detected for each source in positive and negative modes.

Ionization source	α-Pinene		Limonene	
APCI	646 (+)	503(-)	1321(+)	1346(-)
HESI	594(+)	693(-)	1017(+)	1864(-)

Each combination of ionization sources and polarity generated a set of chemical formulae. To make a meaningful comparison between the positive and negative ions data, the chemical formulae used were the precursors of the ions identified in the mass spectra. These sets have common data, but also specific chemical formulae. For a given ionization source, less than 50% of the chemical formulae are common to both polarities. In other words, between 30 and 50% of molecular species are ignored when using a single polarity. It is therefore essential to use both polarities in order to better describe all the species present. The HESI source data were compared to the APCI data (Tables 2 and 3), showing an increase of the number of chemical formulae detected by 20 to 30%. This increase is characterized by a better detection of negatively ionized species and those with a higher unsaturation number (DBE). In order to evaluate further the interest for using these ionization sources, we compiled these data in Venn diagrams and proposed a visualization of these sets with a van Krevelen representation; we added the number of DBE in the third dimension. These results are presented in Tables 2 and 3.

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In positive ionization mode, independently of the ionization source and in addition to the common molecular formulae, we detected products with an O/C ratio < 0.2 whereas in the negative ionization mode, we detected molecular formulae with an O/C ratio > 0.5. In addition to these observations, we noted that HESI is more appropriate for studying products with a large number of unsaturation (DBE > 5). Finally, for an optimal detection of the oxidation products, it is necessary to consider the transmission limits of the C-Trap. Here, we could increase by more than 60% the number of molecular formulae detected using several mass ranges for data acquisition. The most appropriate ionization polarity to be used is tight to chemical functions present in products to be detected. We could increase by 30 to 100% the number of chemical formulae detected by using both positive and negative ionization modes. The ionization source used is also important. We could increase the number of detected chemical formulae by 20 to 30% using HESI. We believe that this approach to data validation and these results, although specific to this study, are applicable to any characterization by Orbitrap.

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Table 2. Representation of the mass spectrometry data characterizing the oxidation of α-pinene and limonene (ionization source: APCI positive and negative mode, JSR experiments).

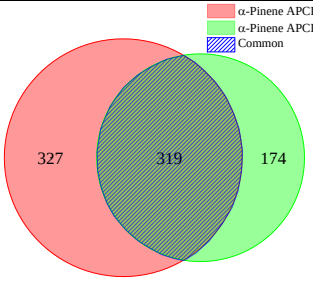
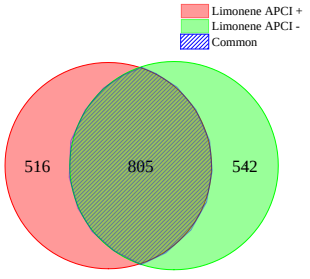
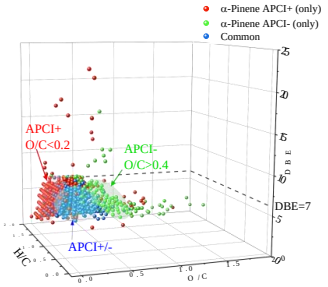
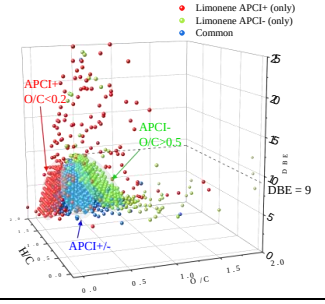
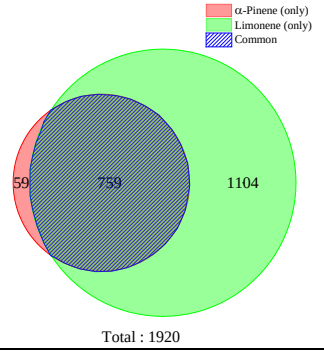
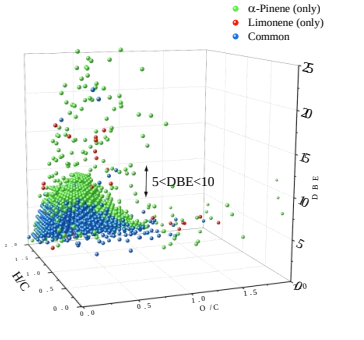
	α-Pinene			**Limonene**		
Source and mode	**APCI$^+$**		**APCI$^-$**	**APCI$^+$**		**APCI$^-$**
Number of compounds	646		503	1321		1346
Distribution	specific to positive mode 327	common 319	specific to negative mode 174	specific to positive mode 516	common 805	specific to negative mode 542
Venn graph						
VK *vs* DBE						
						

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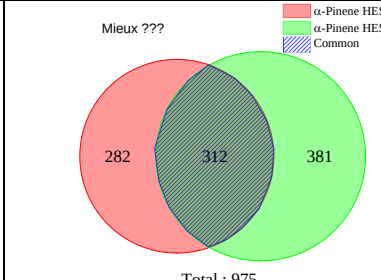
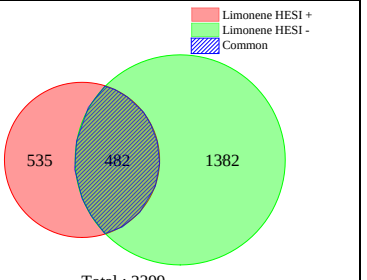
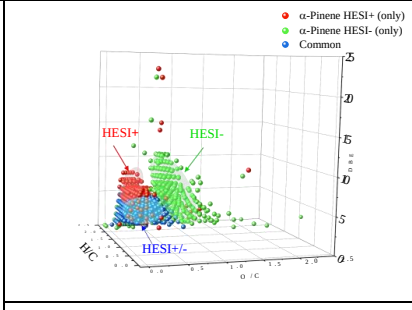
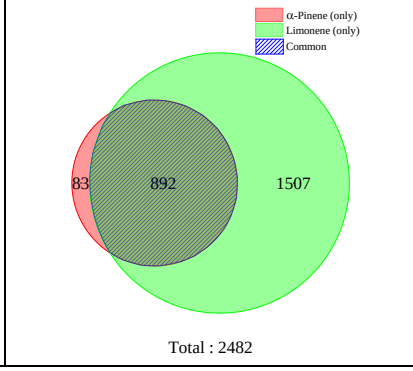
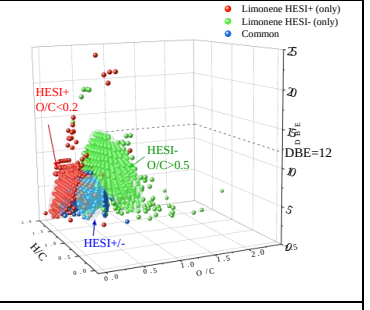
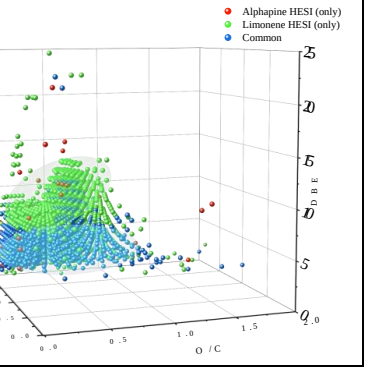
Table 3. Representation of the mass spectrometry data characterizing the oxidation of α-pinene and limonene (ionization source: HESI positive and negative modes, JSR experiments).

	α-Pinene			Limonene		
Source and mode	HESI$^+$		HESI$^-$	HESI$^+$		HESI$^-$
Number of compounds	594		603	1017		1864
Distribution	specific to positive mode 282	common 312	specific to negative mode 381	specific to positive mode 353	common 482	specific to negative mode 1342
Venn Graph						
VK *vs* DBE	 			 		

4.2 Autoxidation products detected in a JSR

In order to compare the oxidation of α-pinene and limonene, we compiled the positive and negative ionization data obtained with APCI (Table 2) and HESI (Table 3) ionization sources to obtain a more exhaustive database. For the APCI and HESI sources, we distinguished three datasets, two of which are specific to the oxidation of α-pinene

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and limonene and one which is common to both isomers. In the following, the name "only" will be used to describe the molecules specific to the oxidation of one of the terpene isomers. This common dataset represents more than 90% of the chemical formulae identified in α-pinene oxidation samples, detected with both APCI and HESI. For limonene, where the number of identified chemical formulae is greater, this common dataset ranges between 68% in APCI and 37% in HESI. In these two cases, the relatively low residence time (2 seconds) and the diversity of the chemical formulae obtained show that the oxidation of these two terpene isomers leads to the opening of the ring, a phenomenon also observed in atmospheric chemistry (Berndt et al., 2016;Zhao et al., 2018;Iyer et al., 2021). Concerning the products' molecular formulae common to both isomers, figure 1 shows that they are limited to 10 oxygen atoms. This limit is linked to α-pinene whose oxidation beyond 10 oxygen atoms remains weak (less than 2% of the totality of the identified molecules for this isomer). The autoxidation will allow keeping this similarity in the different steps of the oxidation by simple addition of two atoms of oxygen. In the case of limonene, the presence of an exocyclic double bond will increase, in a similar way to atmospheric chemistry (Kundu et al., 2012), the possibilities of oxidation and accretion. It remains however impossible, considering the size of the whole and the diversity of the isomers, to formalize all the reaction mechanisms. Nevertheless, the formation of oxidized species can be described with the help of graphical tools. The dispersion of the number of oxygen atoms per molecule shows for example that limonene oxidizes more than α-pinene (Tables 2 and 3). In the case of limonene, with a HESI source, an oxygen number of up to 15 is measured, with maximum counts recorded for 10 O-atoms (Fig. 1), whereas it remains mostly less than or equal to 10 for α-pinene (Fig. 1). Moreover, this graph shows, for the products specific of limonene oxidation, a distribution centered on 11 oxygen atoms with carbon skeletons probably resulting from accretion.

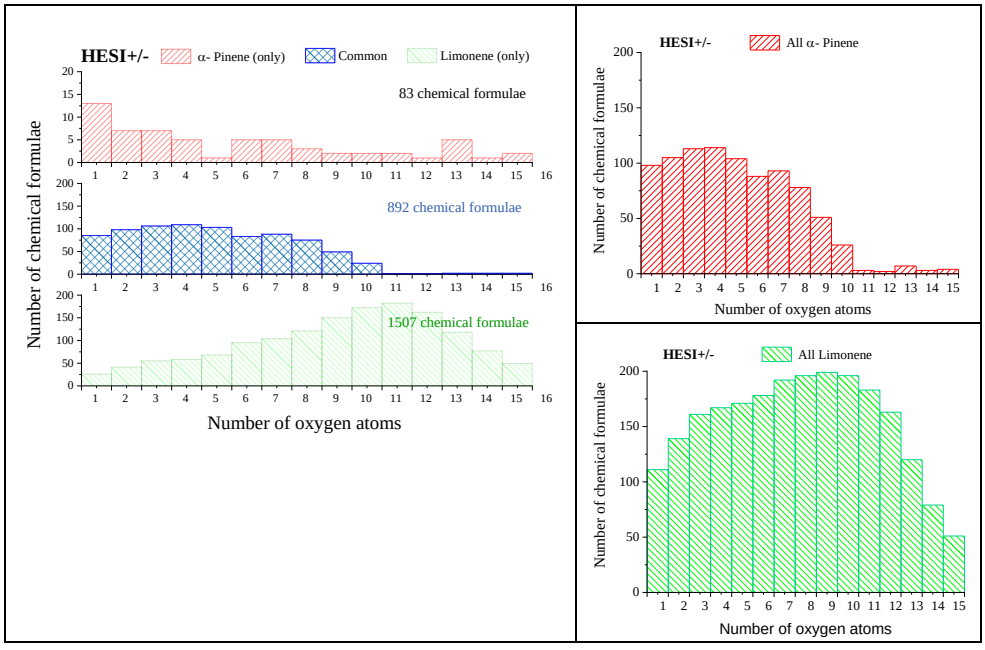

Figure 1: Distribution of α-pinene and limonene autoxidation products as a function of their oxygen content (ionization source: HESI, combined positive and negative modes data).

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To verify this accretion hypothesis, we can plot the OSc as a function of the number of carbon atoms or the O/C ratio at fixed number of C-atoms (Fig. 2). One can visualize the evolution of the molecular oxidation for each carbon skeleton and the formation of oligomers. Species that are unique to one of the isomers, or common to both are differentiated using different colors. In addition to the autoxidation represented by the vertical axes for a given number of carbon atoms (Fig. 2a), we observe mechanisms of fragmentation, accretion and oligomerization between the carbon skeleton. These reaction mechanisms contribute to forming families according to the rate of oxidation and the size of their carbon skeleton. The increase in the number of oxygen atoms, but also of carbon atoms will decrease products volatility. We distinguish four families: low volatile oxygenated organic aerosols (LV-OOA), semi-volatile oxygenated organic aerosols (SV-OOA), biomass burning organic aerosols (BBOA) and water-soluble organic carbons (WSOC) following a classification proposed in the literature (Kroll et al., 2011). If we analyze the two sets of molecules from the APCI and HESI sources, positive and negative ionization modes combined, we find that nearly 73% of the molecules are linked to each other by a single difference of 2 oxygen atoms which reflects an autoxidation mechanism (Fig. 3).

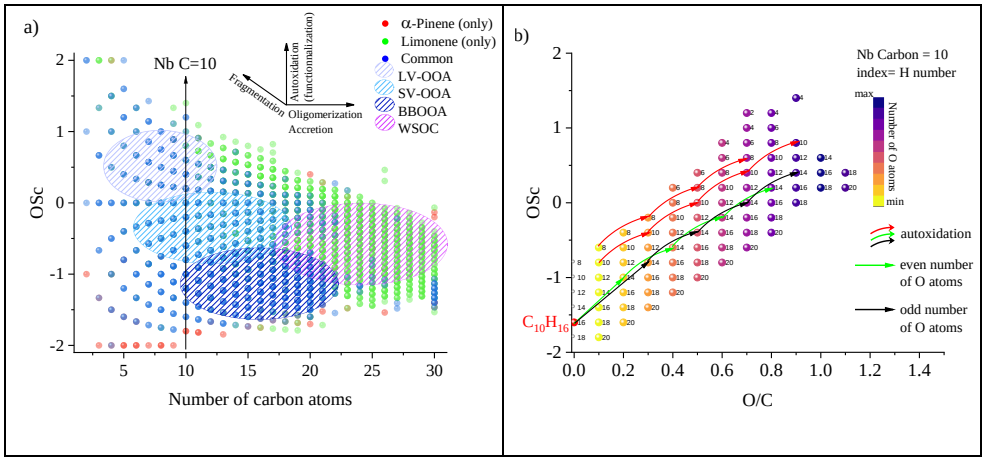

Figure 2: Overview of the distribution of limonene and α-pinene oxidation products observed in a JSR: (a) OSc versus carbon number in detected chemical formulae from APCI and HESI data. (b) OSc versus O/C atomic ratio for a carbon number of 10; index of the products: number of hydrogen atoms. Arrows indicate autoxidation from a C_6H_{16} isomer, according to the oxygen parity in products.

We can measure the amplitude of autoxidation for each carbon skeleton from the OSc vs. O/C space. For the two isomers, for which the initial carbon number (C) is equal to 10, one can observe (Fig. 2b) two autoxidation routes with an even and odd number of oxygen atoms. This parity distinction is initially present for the two main radicals, $ROO^{\cdot}$ and $RO^{\cdot}$, responsible for autoxidation. However, the termination and propagation reactions will change the oxygen parity to form a new distribution where the parity links between radicals and molecules are lost, making any interpretation of radical oxidation route impossible (Fig. 3). The autoxidation mechanisms indicated by arrows in Figure 2b characterize systematic hydroperoxy chain terminations which do not change oxygen parity. HESI data showed an equivalent distribution of the two oxygen parities in molecular products (odd: 51%; even 49%) therefore confirming a lack of selectivity of the reaction mechanisms with respect to the parity of the radicals.

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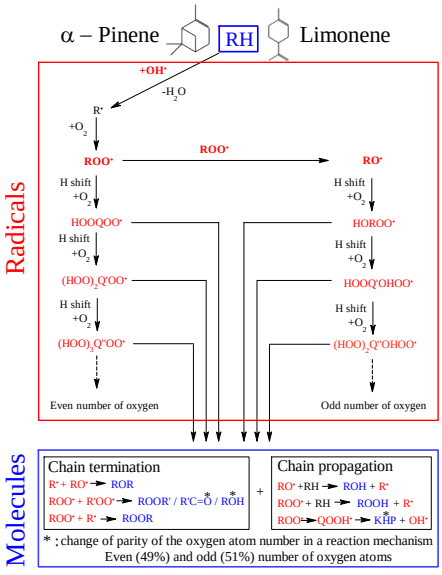

Figure 3: Autoxidation reaction mechanisms in combustion (left) and in the atmosphere (left and right). * indicates a change in number of oxygen atoms.

4.3 Combustion versus atmospheric oxidation

We have explored potential chemical pathways related to autoxidation in the previous section. For this purpose, we have performed experiments under cool flame conditions (590 K). This autoxidation mechanism is also present in atmospheric chemistry, but it is only recently that it has been found that this mechanism could be one of the main formation pathways for SOA (Savee et al., 2015). Studies have described this mechanism in the case of atmospheric chemistry with the identification of radicals and molecular species (Tomaz et al., 2021). However, previous studies of the propagation of this reaction mechanism are mainly focused on the initial skeletons of the 10-carbon isomers, whereas the other carbon skeletons are also concerned by autoxidation. It is therefore useful to evaluate the proportion of products of autoxidation among the total species formed.

We propose a new approach which consists in assessing a set of molecules mainly resulting from autoxidation against different sets of experimental studies related to atmospheric chemistry. The objective is to compare the similarity between these conditions on the basis of autoxidation by considering different experimental parameters chosen for their diversity. For this purpose, we selected, a HESI ionization source, better adapted to the electronegativity of the oxidized molecules, as well as to higher m/z. Moreover, we have already shown in this paper that the HESI (+/-) ionization source is better suited for detecting autoxidation products (detection of 96% of the total chemical formulae observed in autoxidation).

Among published atmospheric chemistry studies of terpenes oxidation, we have selected 15 studies, 4 for α-pinene and 11 for limonene. The data were acquired using different experimental procedures (methods of oxidation, techniques of characterization). Table 4 summarizes all the experimental parameters related to the selected studies.

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Table 4. Experimental settings of 15 oxidation studies of two terpenes under atmospheric conditions and cool flames.

Reference	Oxidation mode	Sampling	Experimental setup	Concentrations of reactants	Ionization /source	Instrument	Chemical formulae
α-Pinene							
Y. Deng et al. (2021)	Dark ozonolysis seed particles OH scavenger	online	Teflon bag; 0.7m3	3.3±0.6 ncps $ppbv^{-1}$ α -Pinene	ESI	ToF-MS	351
Quéléver et al. (2019)	Ozonolysis	online	Teflon bag 5 m^3	10 & 50 ppb α -Pinene	NO_3^- (CI)	CI-APi-TOF	68
Meusinger et al. (2017)	Dark Ozonolysis OH scavenger no seed particles	offline	Teflon bag 4.5 m^3	60 ppb α -Pinene	Proton transfer	PTR-MS-ToF	153
Krechmer at al. (2016)	Ozonolysis	offline	PAM Oxidation reactor	Field measurement	ESI (-) and NO_3^- (CI)	CI-IMS-ToF	43
This work	Cool-flame autoxidation	offline	jet-stirred reactor	1%, α -Pinene No ozone	APCI(3kV) HESI (3kV)	Orbitrap® Q-Exactive	820 (APCI) 975 (HESI)
Limonene							
Krechmer et al. (2016)	Ozonolysis	offline	PAM Oxidation reactor	not specified	ESI (-) and NO_3^- (CI)	CI-IMS-ToF	63
Tomaz et al. (2021)	Ozonolysis	online	flow tube reactor (18 L)	45-227 ppb limonene	NO_3^- (CI) - Neg	Orbitrap® Q-Exactive	282
Fang et al. (2017)	OH-initiated photooxidation dark ozonolysis	online	smog chamber	900–1500 ppb limonene	UV; 10 eV	Time-of-Flight (ToF)	17
Witkowski and Gierczak (2017)	Dark ozonolysis	offline	flow reactor	2 ppm, limonene	ESI,4.5 kV	Triple quadrupole	12
(Jokinen et al., 2015a)	Ozonolysis	online	flow glass tube	1–10000 $x10^9$ $molec.cm^{-3}$, limonene	chemical ionization	Time-of-Flight (ToF)	11
Nørgaard et al. (2013)	Ozone (plasma)	online	direct on the support	850 ppb ozone 15-150 ppb limonene	plasma	Quadrupole time-of-flight (QToF)	29
Bateman et al. (2009)	Dark and UV radiations ozonolysis	offline	Teflon FEP reaction chamber	1 ppm ozone 1 ppm limonene	modified ESI (+/-)	LTQ-Orbitrap Hybrid Mass (ESI)	924
Walser et al. (2008)	Dark ozonolysis	offline	Teflon FEP reaction chamber	1-10 ppm ozone 10 ppm limonene	ESI (+/-); 4.5 kV	LTQ-Orbitrap Hybrid Mass (ESI)	465
Warscheid and Hoffmann (2001)	Ozonolysis	online	Smog chamber	300-500 ppb limonene	APCI; 3kV	Quadrupole ion trap mass	21
Hammes et al., (2019)	Dark ozonolysis	online	flow reactor	15, 40, 150 ppb limonene	^{210} Po α-	HR-ToF-CIMS	20
Kundu et al. (2012)	Dark ozonolysis	offline	Teflon reaction chamber	250 ppb ozone 500 ppb limonene	ESI; 3.7 and 4 kV	LTQ FT Ultra, Thermo Sct (ESI)	1199
This work	Cool-flame autoxidation	offline	jet-stirred reactor	1%, limonene No ozone	APCI(3kV) HESI (3kV)	Orbitrap® Q-Exactive	1863(APCI) 2399(HESI)

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The data are from the articles or files provided in the supporting information S2. In these studies, oxidation was performed only by ozonolysis with different experimental conditions that gather the main methods described in the literature: ozonolysis, dark ozonolysis, ozonolysis with OH scavenger, ozonolysis with or without seed particles. We considered that the methods of analysis by mass spectrometry did not modify the nature of the chemical species but only their relative importance, because of the type of ionization and the sensitivity of the instruments. The combination of data obtained using (+/-) HESI gives a rather complete picture of the autoxidation products.

First, we compared the data from ozonolysis studies of each terpene and identified similarities through the Venn diagram. For studies with two ionization sources, duplicate chemical formulae were removed. We selected the three most representative studies, by the number of the chemical formulae detected. Then, we compared the set of chemical formulae identified after ozonolysis to those produced in low-temperature combustion, the objective being (i) to highlight similarities in terms of products generated by the two oxidation modes and (ii) to identify data resulting from autoxidation.

For α-pinene oxidation, the four studies identified 566 chemical formulae, all polarities combined. Only the study by(Meusinger et al., 2017)was performed in positive mode and none of the studies reported data obtained with two ionization modes (+/–). For limonene oxidation, the three studies identified 1862 chemical formulae. Only the studies by (Walser et al., 2008;Bateman et al., 2009) used (+) and (–) ionization modes. In the case of limonene, oxidation for which accretion is more important than for α-pinene, and for which a greater number of chemical formulae were identified, the similarities is more important. These results are presented in Figure 4 where the ionization polarity used in each study is specified.

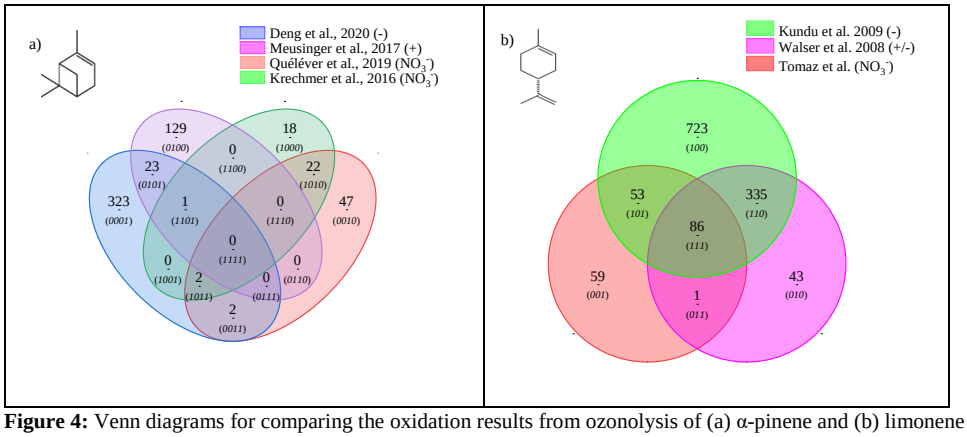

Figure 4: Venn diagrams for comparing the oxidation results from ozonolysis of (a) α-pinene and (b) limonene (see conditions in Table 1). Each digit of the binary numbers in parentheses identifies the datasets being compared.

For α-pinene, no global similarity is observed for the detected chemical formulae. Different hypotheses can be offered to explain this result. Among them, the number of chemical formulae identified per study remains limited (a few dozen to several hundred) and these small datasets are sometimes restricted to specific mass ranges (e.g.

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(Quéléver et al., 2019): C_{10} to C_{20}). In the case of studies carried out with an NO_3^- source, sensitive to HOMS, produced preferentially by autoxidation, we note that nearly 50% of the chemical formulae (10/22) are linked by a simple difference of 2 oxygen atoms.

For limonene, 86 chemical formulae are common to the three studies considered here. In this dataset, nearly 43% of the chemical formulae present a relation similar to that of autoxidation (simple difference of two oxygen atoms) with less than 5% of fragments (Nb C<10). This result seems to indicate that autoxidation dominates.

One can then ask if reaction mechanisms common to atmospheric and combustion chemistry can generate, despite radically different experimental conditions, a set of common chemical formulae and if in this common dataset, a common link, characteristic of autoxidation, is observable?

To address that question, we compared all the previous results, for each of these terpenes to those obtained under the present combustion study. The comparisons were made using the HESI. One should remember that the oxidation conditions in a JSR were chosen in order to maximize low-temperature autoxidation. Again, we used Venn diagrams to analyze these datasets composed of 1590 chemical formulae in the case of α-pinene and 2857 chemical formulae in the case of limonene. The results of these analyses are presented in Figure 5.

It turned out that 301 chemical formulae were identified for α-pinene and 735 chemical formulae for limonene to be common to oxidation by ozonolysis and combustion. This represents 31% of the chemical formulae for the ozonolysis of α-pinene and 31% for those of limonene ozonolysis. For α-pinene, the similarities compared to combustion are specific to each study: (Deng et al., 2021) 69% (Meusinger et al., 2017) 46% (Quéléver et al., 2019)7% (Krechmer et al., 2016) 23%. Chemical formulae common to all studies were not identified. This lack of similarity may be due to a partial characterization of the chemical formulae, a weaker oxidation of α-pinene with an ionization mode less favorable to low molecular weights.

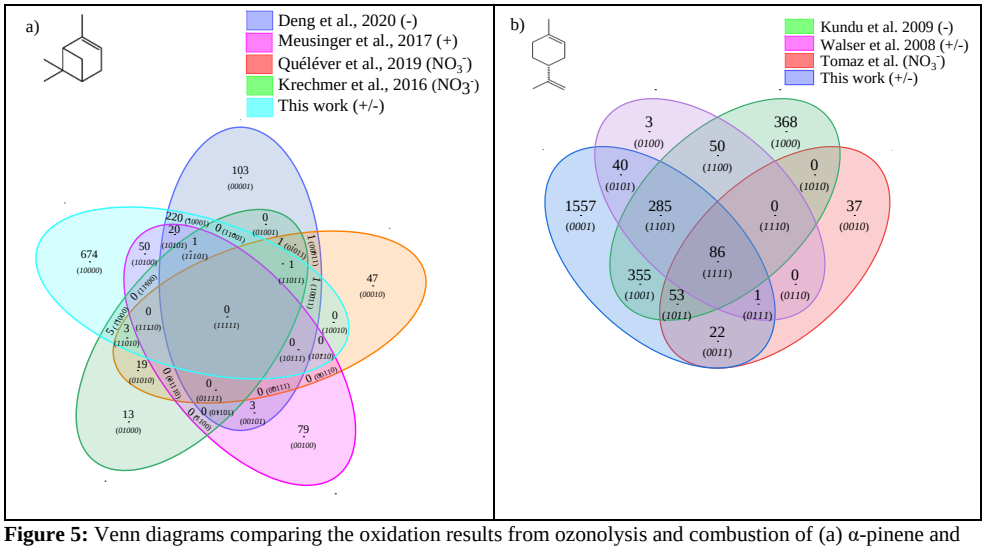

Figure 5: Venn diagrams comparing the oxidation results from ozonolysis and combustion of (a) α-pinene and (b) limonene (see conditions in Table 1).

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For limonene, the similarities with combustion are more important and less spread out. They represent for the different studies: (Kundu et al., 2012) 65% (Walser et al., 2008) 88% (Tomaz et al., 2021) 81%. Moreover, there is a common dataset of 86 chemical formulae which can derive from autoxidation mechanisms. It is necessary to specify again that different reaction mechanisms can cause the observed similarities. However, the preponderance of autoxidation in so-called cold flame combustion is obvious, and in atmospheric chemistry, this reaction mechanism remains competitive or dominates (Crounse et al., 2013;Jokinen et al., 2014b). If we search for an autoxidation link between these 86 chemical formulae, we observe that 43% of these chemical formulae meet this condition: difference of two oxygen atoms, at constant number of carbon and hydrogen atoms. More precisely, these molecules are centered in a van Krevelen diagram on the ratios O/C=0.6 and H/C=1.6, in the range 0.25 < O/C < 0.8 and 1.25 < H/C < 1.85. All oxidized molecules associated with this dataset are presented in Figure 6. The dispersion of the chemical formulae, far from being random, remains consistent with an autoxidation mechanism where the number of carbon atoms is constant.

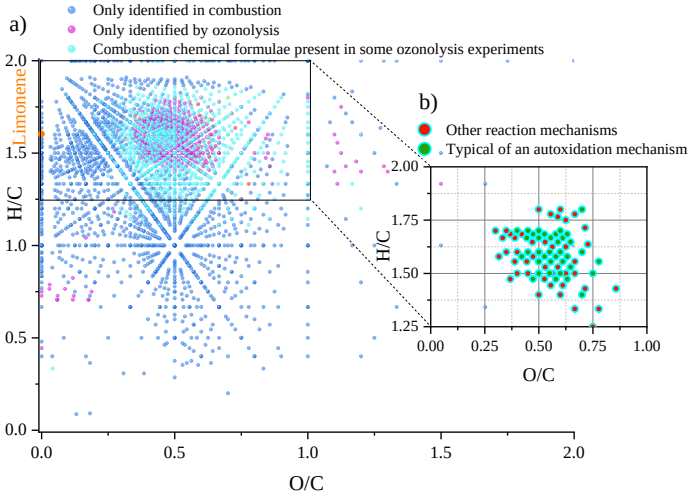

Figure 6: Van Krevelen diagram showing specific and common chemical formulae detected after to oxidation of limonene by ozonolysis and combustion.

A 3-D representation of all limonene oxidation data is given in Fig. S1 (Supplement) where DBE is used as third dimension. From that figure, one can note that products with higher DBE are preferably formed under JSR conditions, i.e. at elevated temperature. The corresponding chemical formulae could correspond to carbonyls and / or cyclic ethers (˙QOOH → carbonyl + alkene + OH and / or cyclic ether + OH).

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Specificities and similarities of these two oxidation modes were further investigated by plotting the distribution of the number of oxygen atoms in detected chemical formulae (Fig. 7). Indeed, the distribution of the number of oxygen atoms allows, in addition to the Van Krevelen diagram, to provide some additional details on these two modes of oxidation. It is in ozonolysis that we observe the chemical formulae having the largest number of oxygen atoms. There, oxidation proceeds over a long reaction time where the phenomenon of aging appears by promoting accretion or oligomerization. One should keep in mind that a short residence time (2 s) was used in JSR experiments. A short residence time should limit accretion which is favored under simulated atmospheric oxidation experiments performed over long reaction times. In combustion, the number of oxygen atoms remains limited to 18, with a lower number of detected chemical formulae compared to the case of ozonolysis. However, it is in combustion that we observe the highest O/C ratios, indicating the formation of the most oxidized products. This difference, however, does not affect the similarities between the chemical formulae detected in the two modes of oxidation. Finally, the analysis of the parities in oxygen atoms, very similar to the three datasets, confirms that the reaction mechanisms presented in Figure 3 do not allow a simple link to be established between the parity of radicals and that of molecular products.

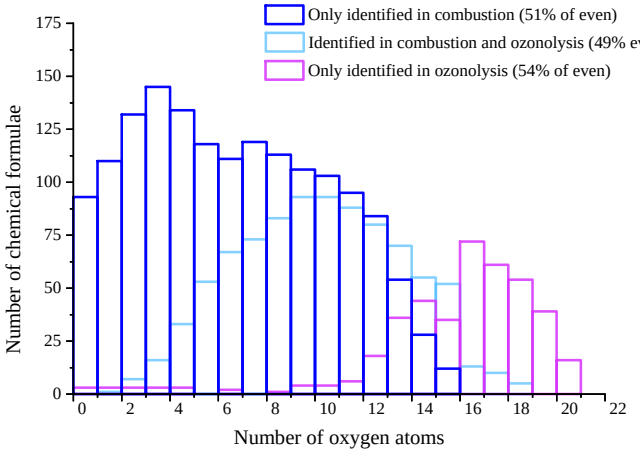

Figure 7: Oxygen number distribution for all the molecules identified for the oxidation of limonene: only in combustion, only in ozonolysis and common to both processes. For each of these distributions, the parity in oxygen number is specified

5 Conclusion

We have analyzed and compared, thanks to different mathematical and visualization tools, the oxidation of α-pinene and limonene under simulated tropospheric and low-temperature oxidation conditions. We have restricted the field of this study to organic compounds ($C_nH_yO_z$) in order to study specifically autoxidation. This work is in the continuity of recently published studies which established the importance of autoxidation under tropospheric oxidation and low-temperature combustion conditions. Faced with the analytical limits of the chemical speciation of thousands of molecules, and in order to complete the work carried out on the reaction mechanisms of the first steps of oxidation, we have developed a global approach based on the study of families of chemical compounds present in these large sets (van Krevelen diagram, oxygen number distribution, oxidation state of carbon -OSc,

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chemical relationship between molecules). We selected existing databases on ozonolysis with a purposive diversity of experimental conditions and compared these data to those obtained in low-temperature combustion conditions where autoxidation is important (cool flame combustion at 590 K). We showed that a significant portion of the chemical formulae were common to both atmospheric and combustion products. Surprisingly, the numerous oxidation mechanisms and the isomerization of chemical species proceeding under these two conditions did not lead to diverging data, but, on the contrary, to similarities. More than 35% of the chemical formulae detected in combustion chemistry experiments using a JSR have been detected in the studies carried out under atmospheric conditions. Finally, we have outlined the existence of a substantial common dataset of autoxidation products. This result tends to show that autoxidation is indeed inducing similarity between atmospheric and combustion products.

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