Epoxide as a Precursor to Secondary Organic Aerosol Formation from Isoprene Photooxidation in the Presence of Nitrogen Oxides

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Author contributions: Y.-H.L., H. Z., H.O.T.P., E.O.E., L.J.B., A.G., J.D.S. designed research; Y.-H.L., H.Z., H.O.T.P., Z.Z., W.J.M., S.P., M.A., T.C., S.H.B., K.G.S., Y.X., D.J.L., I.R.P., E.O.E., L.J.B., A.G., J.D.S. performed research; Y.-H.L., H.Z., H.O.T.P., Z.Z., W.V., D.J.L., I.R.P., E.O.E., L.J.B., A.G., J.D.S. analyzed data; Y.-H.L., H.Z., H.O.T.P., E.O.E., L.J.B., A.G., and J.D.S. wrote paper.

The authors declare no conflict of interest.

For Submission To: Proceedings of the National Academy of Sciences (PNAS) USA

Classification: PHYSICAL SCIENCES (major area): Environmental Sciences (minor area)

Manuscript Information: Number of Text Pages – 23 (includes references and figure legends); Number of Figures – 5

Abstract

Isoprene is a substantial contributor to the global secondary organic aerosol (SOA) burden, with implications for public health and the climate system. The mechanism by which isoprene-derived SOA is formed and the influence of environmental conditions, however, remain unclear. We present evidence from controlled smog chamber experiments and field measurements that in the presence of high levels of nitrogen oxides (NO_x = NO + NO_2) typical of urban atmospheres, 2-methyloxirane-2-carboxylic acid (methacrylic acid epoxide; MAE) is a precursor to known isoprene-derived SOA tracers, and ultimately to SOA. We propose that MAE arises from decomposition of the OH adduct of methacryloylperoxynitrate (HOMPAN). This hypothesis is supported by the similarity of SOA constituents derived from MAE to those from photooxidation of isoprene, methacrolein, and MPAN under high-NO_x conditions. Strong support is further derived from computational chemistry calculations and Community Multiscale Air Quality (CMAQ) model simulations, yielding predictions consistent with field observations. Field measurements taken in Chapel Hill, NC, considered along with the modeling results indicate the atmospheric significance and relevance of MAE chemistry across the U.S., especially in urban areas heavily impacted by isoprene emissions. Identification of MAE implies a major role of atmospheric epoxides in forming SOA from isoprene photooxidation. Updating current atmospheric modeling frameworks with MAE chemistry could improve the way that SOA has been attributed to isoprene based on ambient tracer measurements, and lead to SOA parameterizations that better capture the dependency of yield on NO_x.

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Introduction

Isoprene (2-methyl-1,3-butadiene, C_5H_8) is released by terrestrial vegetation in an estimated quantity of 600 Tg-yr^{-1} (1) and represents the largest single non-methane hydrocarbon emission into Earth's atmosphere. Photooxidation of isoprene by hydroxyl radicals (OH) during the daytime (2) has been identified as a source of tropospheric ozone (O_3) (3) and secondary organic aerosol (SOA) (4-11). Recent work has shown that anthropogenic pollutants, particularly mixtures of nitrogen oxides (NO_x = NO + NO_2) and sulfur dioxide (SO_2), greatly enhance isoprene as a source of SOA (5, 6, 8, 10, 11). While isoprene is thought to be a substantial contributor to global SOA (12, 13), the mechanism by which isoprene-derived SOA is formed and the influence of environmental conditions on SOA formation remain unclear, but are critical to developing $PM_{2.5}$ control strategies for protection of public health and to assessing the impact on the climate system. Community Multiscale Air Quality (CMAQ) model simulations indicate that removal of controllable anthropogenic emissions could affect a reduction of greater than 50% in biogenic SOA in the eastern U.S. (14).

NO_x-dependent chemical pathways have been proposed to explain isoprene-derived SOA tracers common to both laboratory-generated and organic aerosols in atmospheres typical of the urban environment (15). SOA formation from isoprene under high-NO_x conditions has been ascribed to the oxidation of methacryloylperoxynitrate (MPAN) (10, 16), which laboratory studies have established as a second-generation oxidation product of isoprene (17, 18). High NO_2/NO ratios favor formation of MPAN from both isoprene and methacrolein (MACR) photooxidation and result in enhanced SOA yields (10, 16). Identification of similar chemical constituents in SOA produced from the photooxidation of isoprene, MACR, and MPAN further

supports the central role of MPAN oxidation under these conditions (10). Mass spectrometric analysis of oligoesters and their mono nitrated and sulfated derivatives from SOA generated in the high NO_2/NO chamber experiments yields a series of product ions separated by 102 Da, suggesting a common monomeric unit. While a mechanism of oligoester formation remains to be determined, the observation of a common monomeric unit is in accord with a critical single gas-phase intermediate from MPAN photooxidation as an oligoester precursor (10).

The mechanism proposed in Fig. 1 for SOA formation from the photooxidation of isoprene in the presence of NO_x shows the published route to MPAN via the H-abstraction channel of the branching reaction of MACR with OH (17-19). The fate of the transient resulting from the addition of OH to MPAN, however, has until recently been a matter of conjecture. Kjaergaard et al. (20) have reported a computational study suggesting that the HOMPAN transient adduct reacts by elimination of nitrate radical (NO_3) followed by an intramolecular rearrangement to hydroxymethylmethyl-α-lactone (HMML), which is suggested as the precursor of known high-NO_x SOA compounds and oligoesters. In Fig. 1 we suggest a second parallel, thermodynamically feasible pathway via rearrangement of HOMPAN to methacrylic acid epoxide (MAE), which yields known high-NO_x SOA marker compounds and oligoesters similar to those previously reported from photooxidation of isoprene, MACR, and MPAN (10, 16, 21). This study presents experimental evidence supported by computational and modeling studies that the most likely route for isoprene-derived SOA under high-NO_x conditions is via the gas-phase intramolecular rearrangement of the HOMPAN adduct to MAE followed by reactive uptake. We have detected gaseous MAE in the local environment, and modeling of MAE production on a local scale is in accord with measured concentrations. Chemical transport modeling of ambient concentrations of gaseous MAE on a large scale over the southeastern U.S. demonstrates a

potentially significant contribution of MAE to SOA in regions where isoprene emissions interact with anthropogenic pollutants. Taken together, the results present a coherent picture that strongly supports MAE as a critical intermediate leading to SOA formation from isoprene photooxidation in the presence of NO_x and fills in an important step in the pathway to SOA under conditions where biogenic and anthropogenic emissions interact.

Results and Discussion

MAE from the Photooxidation of MACR in Presence of NO_x. The photooxidation of MACR to MAE is confirmed by controlled outdoor smog chamber experiments conducted under the irradiation of natural sunlight at ambient temperature in the presence of NO_x. Initial concentrations of MACR (1 ppmv), NO (400 ppbv) and NO_2 (200 ppbv) were set for optimization of MPAN formation and generation of sufficient oxidation products for off-line chemical analysis based on simulations from a one-dimensional box model (see *SI Text*). Gas-phase samples were collected hourly with two fritted glass bubblers connected in series and preceded by a Teflon filter to remove aerosol. Ethyl acetate was selected as an aprotic collection solvent to avoid the possibility of MAE hydrolysis and the collection train was cooled in an ice bath to minimize the evaporation of solvent and volatile products. The bubbler samples were analyzed by ultra performance liquid chromatography interfaced to a high-resolution quadrupole time-of-flight mass spectrometer equipped with an electrospray ionization source (UPLC/ESI-HR-Q-TOFMS) operated in the negative ion mode. The extracted ion chromatograms (EICs) at the nominal mass of the MAE anion, *m/z* 101, are compared in Fig. 2. The EIC in Fig. 2*A* is from a MACR/NO_x photooxidation experiment and in Fig. 2*B* from an authentic MAE standard in ethyl acetate, which both show a single major peak with an identical retention time. The accurate

mass of the extracted ion at *m/z* 101 corresponds to the composition of the MAE anion ($C_4H_5O_3^-$) within ± 1 mDa for both the bubbler sample and the MAE standard.

The quantitative time profile of MAE formation during the course of an MACR photooxidation experiment (Fig. S1) shows that the increase in gaseous MAE tracks with particle nucleation and growth. Since no seed aerosol was introduced into the chamber prior to the experiment, the increase of aerosol mass concentration can be ascribed to nucleation of MAE followed by heterogeneous oxirane ring-opening reactions. Off-line UPLC/ESI-HR-Q-TOFMS analysis of the nucleated aerosol collected on the Teflon filter preceding the tandem bubblers is in accord with this contention. The collected material is comprised primarily of higher order oligoesters with MAE as a common monomeric unit (Table S1), consistent with the high-NO_x MPAN SOA constituents reported in Surratt et al. (10) and high-NO_x MACR SOA constituents reported by other investigators (16, 22), and thus consistent with MAE as the intermediate involved in SOA formation in these experiments.

Gas chromatography/flame ionization detection data indicated that complete reaction of MACR was coincident with peak MAE concentration (Fig. S1), and analysis of the back-up bubbler for breakthrough indicated a collection efficiency of 86% for gas-phase MAE. MAE rapidly converts to particle mass and assuming MAE contributes 50–80% of the measured SOA mass in the chamber experiment (8), a range of values for the chamber-based MAE yield was determined. The total MAE mass concentration profile was estimated by summing the mass concentrations of MAE in the particle and gas phases as a function of time for the 50 and 80% contributions. For each total mass contribution, an initial value for the MAE yield was selected and the time profile of the MAE concentration computed using the SAPRC07 chemical mechanism in a one-dimensional box model to obtain the molar yield of MAE. The procedure

was repeated, varying the MAE yield until the predicted MAE mass concentration time profile was in agreement with the chamber profile (see Fig. S2). The final MAE yields for the 50 and 80% mass contributions provide lower and upper bounds of 0.18 and 0.32, respectively, for the reaction of OH + MPAN to form MAE. See *SI Text* for further details.

Reactive Uptake of MAE onto Acidified Sulfate Aerosol. The Kleindienst et al. (23) tracer-based source apportionment method uses 2-methylglyceric acid (2-MG) as an isoprene SOA tracer. We are able to provide insight into the mechanism of 2-MG formation by dark reactive uptake of MAE onto preexisting seed aerosols (see Table S2). Fig. S3 demonstrates that the uptake of synthetic MAE onto acidified sulfate aerosols yields substantial SOA mass, while uptake onto preexisting neutral sulfate seed aerosol is negligible. Fig. 3 shows that 2-MG is a component of SOA formed from the reactive uptake of MAE onto pre-existing acidified sulfate aerosol and has also been identified in SOA generated by the photochemical oxidation of both isoprene and MACR in the presence of NO_x, and in $PM_{2.5}$ collected from downtown Atlanta, GA, on August 9, 2008, at an $[NO_2]/[NO]$ ratio of 5.14 (22). Other high-NO_x SOA tracers, such as the sulfate ester of 2-MG (Fig. S4), as well as the 2-MG dimer (24), have also been observed in these systems. The origin of the markers is most readily explained via nucleophilic attack on the oxirane ring of MAE by water to yield 2-MG, SO_4^{2-} to yield 2-MG sulfate, or the carboxylate anion of MAE to yield the 2-MG dimer. Formation of sulfates and oligoesters by acid-catalyzed esterification is kinetically unfavorable under tropospheric conditions (25), and therefore ruled out as a mechanism.

SOA yields (mass of SOA formed/initial MAE concentration) from our reactive uptake experiments are not reported because the uptake behavior of MAE is beyond the scope of the thermal equilibrium partitioning approach, and involves competitive kinetics. Additional work is

required to obtain the reactive uptake coefficients (or reaction probabilities, γ) to determine the heterogeneous removal rate of MAE. The heterogeneous removal rate will likely be highly variable, depending on particle composition, phase, acidity, presence of surfactants, and liquid water content. Once the heterogeneous removal rate has been determined, the current modeling framework can be refined to represent MAE chemistry in SOA models with increased accuracy.

Computational Investigations of the OH + MPAN Reaction Pathway. As a first step in developing a chemical mechanism for the OH + MPAN addition reaction to form SOA from photooxidation of MACR in the presence of NO_x, calculations were carried out to estimate the total rate constant for this reaction and the yields of its products, including MAE. The energy diagram in Fig. 4 was constructed based on our laboratory and field investigations of the formation of MAE from MACR under high-NO_x conditions and the recent report of Kjaergaard et al. (20) on the potential formation of HMML from OH + MPAN. The quantum chemistry codes GAUSSIAN 2009, NEB, a nudged elastic band approach for identifying minimum energy paths, complexes and transition states, and DIMER for refining transition states and their energies, were used to construct the energy diagram (26-29). All of the quantum chemistry calculations were performed with the m062x density functional in GAUSSIAN 2009, using initially the 6-311++g** orbital basis set.

The energy diagram shows the loose and tight transition states, and, as products, the MPAN--OH van der Waals complex, the HOMPAN adduct, and the loosely bound complexes MAE--NO_3, HMML--NO_3, and HAC (hydroxy acetone)--CO--NO_3. The first NEB calculation, carried out between OH + MPAN and HOMPAN revealed a barrierless potential energy curve connecting the loose transition state TS_1, the MPAN--OH van der Waals complex and the tight transition state TS_2. A second NEB calculation between HOMPAN and HAC--CO--NO_3

showed HMML--NO_3, along with the tight TS_4 and TS_6 transition states connecting HOMPAN to HMML--NO_3 and HMML--NO_3 to HAC--CO--NO_3, respectively. Since MAE--NO_3 was an expected intermediate in this reaction, a third NEB calculation was set up between HOMPAN, and HAC--CO--NO_3, but this time with MAE--NO_3 as an intermediate in the initial trajectory. The results of this NEB calculation confirmed the presence of MAE--NO_3 and HMML--NO_3 as well as the tight TS_3, TS_5, and TS_6 transition states. The energy minima in Fig. 4 corresponding to OH + MPAN, MPAN--OH, HOMPAN, MAE--NO_3, HMML--NO_3, and HAC--CO--NO_3 were refined by computing their structures, energies and vibrational frequencies using the maug-cc-pvtz basis set (30). The same level of theory was employed by DIMER to improve those properties for the tight transition states. The optimized zero point energy-corrected electronic energies, relative to the OH + MPAN energy for MPAN--OH, HOMPAN, MAE--NO_3, HMML--NO_3, HAC--CO--NO_3, and the tight transition states are shown in the diagram.

The structures, vibrational frequencies and energies of the reactants and the tight transition states, the fitted Morse parameters for the barrierless potential energy curve, the average energy transfer parameter, and the Lennard–Jones parameters were used as input for VARIFLEX, a widely used chemical kinetics code (31-33), to compute the total rate constant and molar yields for the OH + MPAN reaction at T=300 ºK and P=760 Torr. MPAN--OH, HOMPAN, MAE--NO_3, and HMML--NO_3 were subject to both forward and reverse reactions as well as energy-transferring thermalization collisions with the bath gas N_2. Further details concerning the VARIFLEX calculations can be found in the *SI Text*. Using the computed value of -1.80 kcal mol^{-1} for the TS_2 transition state energy, the total rate constant using VARIFLEX was calculated to be 5.69 x 10^{-12} cm^3 $molecule^{-1}s^{-1}$. This value differs significantly from the experimental value of 3.2 ± 0.8 x 10^{-11} cm^3 $molecule^{-1}s^{-1}$ at T=275 ºK reported by Orlando et al. (18), who noted

their measured rate constant was expected to vary little from the value at 300 ºK. Recent VARIFLEX calculations of rate constants for OH addition to hydrocarbons containing carbon double bonds have revealed similar differences. Greenwald et al. (34) observed for the OH + ethene addition reaction that decreasing the energy of the transition state analogous to TS_2 by 1.0 kcal $kmol^{-1}$, which is within the expected accuracy of their ab initio calculations, results in good agreement with experimental data between 300 and 400 ºK. A similar approach was adopted by Zador et al. (35) in their computational investigations of the OH + propene addition reaction. Consequently, the TS_2 transition state energy in the current study was adjusted to -2.80 kcal mol^{-1} based on the reported improvements in rate constant predictions, and the VARIFLEX calculation was repeated, yielding a rate constant of 3.00×10^{-11} cm^3 $molecules^{-1}sec^{-1}$, in good agreement with the experimental value. We note, however (see *SI Text*), that the change in TS_2 does not significantly impact the product yields. Using the revised TS_2 transition state energy and neglecting the MPAN--OH van der Waals complex because of its shallow energy minimum and low molar yield coefficient MPAN--OH = -3.10×10^{-7}, our calculations suggest the reaction mechanism, with its molar-based product yields, can be expressed as

$$\text{OH + MPAN} \rightarrow 0.19\ \text{HOMPAN} + 0.21\ \text{MAE--NO}_3 + 0.57\ \text{HMML--NO}_3 + 0.03\ \text{HAC--CO--NO}_3 \qquad \textbf{[1]}$$

The VARIFLEX-derived estimate of 0.21 for the yield for MAE is within the range of 0.18–0.32 obtained in the chamber-based method. The major pathway for formation of MAE is the addition of OH radical to MPAN forming the chemically activated HOMPAN adduct. NO_3 then leaves HOMPAN by way of the rate determining transition state TS_3, followed by a hydrogen atom transfer and formation of an epoxide (see *Movie S1* for the calculated reaction). HMML warrants discussion as a potentially significant contributor to SOA as a consequence of its molar yield of

0.57. As a class, α-lactones are highly labile compounds that have not been observed under conditions relevant to the tropospheric environment (36, 37). Additionally, there are no reports of attempts to generate HMML or to determine its reaction products. 2-Oxooxirane, the unsubstituted structural analog of HMML which would be expected to have similar physico-chemical properties, has been generated in the gas phase at 298 K and 100 Torr with a lifetime of ~150 μs (38). The short lifetime of 2-oxooxirane and the data available on α–lactones in general argue against HMML as a major source of SOA. Under atmospheric conditions, thermalized HOMPAN will react with O_2 forming the associated peroxy radical that will undergo further reactions. Additional studies are needed to determine whether these products contribute to SOA formation.

Atmospheric Relevance and Abundance of MAE. The sampling apparatus used for detection of MAE in the smog chamber photooxidation of MACR was assembled outdoors in Chapel Hill, NC, during summer 2012. The EIC at *m/z* 101 from UPLC/ESI-HR-Q-TOFMS analysis of the field sample in Fig. 2*C* shows a peak with a retention time and accurate mass identical to that obtained from the MACR photooxidation under high-NO_x conditions (Fig. 2*A*) and the MAE standard (Fig 2*B*). Taken together with the EICs from the chamber studies, the field samples confirm the presence of MAE in the ambient urban atmosphere. The average daytime concentration of 0.34 μg m^{-3} (0.21–0.75 μg m^{-3}, n=6) and nighttime concentration of 0.16 μg m^{-3} (0.07–0.34 μg m^{-3}, n=6) for gas-phase atmospheric MAE is in accord with expectation for a photochemical oxidation pathway in an area of high isoprene emissions influenced by anthropogenic NO_x, and is strong evidence that MAE is an important intermediate in the high-NO_x photochemistry of isoprene.

Fig. S5 shows the diurnal profile of surface layer gaseous MAE from July 21 to August 20, 2006 predicted by CMAQ after incorporation of gas-phase MAE chemistry into the model. Concentrations of MAE are predicted to increase in the early morning and peak in the afternoon between 3 and 5 PM local time. The predicted concentrations of MAE vary significantly from day-to-day, with afternoon MAE concentrations ranging from 0.05 to 0.25 μg m^{-3}. Noteworthy is the consistency between the CMAQ predicted magnitude and diurnal variation in MAE concentration and field observations from 2012 (Table S2).

Fig. 5 shows the estimated concentration of surface layer gaseous MAE over the continental U.S. predicted by CMAQ during one month (July 21 to August 20) in summer 2006 at 12 km by 12 km horizontal resolution. The highest MAE concentrations reflect locations with high isoprene emissions, as well as significant anthropogenic activity that can provide NO_x to convert isoprene to MPAN. Near Atlanta, GA, MAE concentrations average around 0.1 μg m^{-3} and can reach up to 0.6 μg m^{-3}. Southern California and areas near St. Louis, MO, are also predicted to experience relatively high levels of MAE. In general, concentrations of MAE are predicted to average 0.06 to 0.1 μg m^{-3} across the southeast and near the Ohio River Valley.

Uncertainty in predictions of isoprene emissions arise because of local meteorology as well as the modeling algorithm used to parameterize the emission process. CMAQ simulations in this study use BEIS emissions (39), which can be a factor of 2 lower than MEGAN (1) predictions (40). Thus, the gaseous MAE concentrations may be significantly higher than currently displayed in Fig. 5. Furthermore, an aerosol uptake pathway for MAE has not yet been implemented in the model. Uptake to the aerosol phase could extend the lifetime of MAE by suppressing gas-phase reaction with OH. In addition, uncertainty in NO_x predictions as a result of chemistry and emissions, reflected in a high bias in NO_2 for urban areas and low bias in rural areas (41) as well

as underestimated NO_3 wet deposition (42) in CMAQ, could lead to differences between measured and observed MAE concentrations.

Atmospheric Implications. The results presented here strongly support MAE as the precursor of 2-MG, the ubiquitous SOA tracer of both isoprene and MACR photooxidation under high-NO_x conditions (10, 15). Reactive uptake of MAE by acidified sulfate seed aerosols and atmospheric aerosols (Fig. 3) points to MAE as the major and heretofore-unidentified precursor to SOA derived from isoprene photooxidation in the presence NO_x. Furthermore, the distribution of the predicted mean gaseous MAE (Fig. 5*A*) matches the spatial patterns of enhanced summertime aerosol optical thickness over the southeastern U.S. observed by Goldstein et al. (43) (see *SI Text* for spatial distribution of other isoprene-derived high-NO_x products), likely linking our observations with the dominant summertime regional aerosol and the importance of biogenic volatile organic compound-anthropogenic interactions in radiative forcing in climate models. Taken together with the recent detection of isoprene epoxydiols (IEPOX) under low-NO conditions (9-11), identification of MAE also implies epoxides derived from the oxidation of isoprene play a major role as SOA precursors. With respect to MAE, consistency between the predicted and chamber-based values for the yield of MAE as well as between observed ambient MAE levels and the CMAQ predictions are encouraging, and in accord with a contribution of MAE to secondary organic aerosol. However, additional work to develop a robust database of laboratory measurements of the OH + MPAN rate constant and product yields is needed to fully evaluate the proposed mechanism. Further investigation of the heterogeneous chemistry of MAE is also needed to elucidate the complex gas-particle interactions necessary to understand the kinetics and chemical fate of MAE under different atmospheric conditions, such as aerosol composition, liquid water content, and aerosol acidity.

Materials and Methods

MACR/NO_x Photooxidation Experiments. MACR/NO_x photooxidation experiments were carried out in a fixed volume 120-m^3 Teflon film environmental irradiation chamber, located on the roof of the UNC Gillings School of Global Public Health. Initial conditions for each experiment consisted of 1 ppmv MACR, 0.2 ppmv NO, and 0.4 ppmv NO_2. No seed aerosol was injected into the chamber. All reactants were injected into the chamber before sunrise. Measurements from both gas and particle phases were taken periodically until sunset. Detailed operating conditions for chemical and physical monitoring of the chamber have been previously described (44). To detect gaseous MAE formation, chamber air was continuously drawn through two fritted-glass bubblers in series at a sampling flow rate of ~ 1 L min^{-1}. Bubbler samples were collected in ethyl acetate cooled in an ice bath. Teflon membrane filters (Pall Life Science, 47 mm diameter, 1.0-μm pore size) were installed in front of the inlet to the glass bubblers to ensure collection of gas-phase MAE only. Bubbler samples were collected hourly throughout the course of experiments, and analyzed immediately by UPLC/ESI-HR-Q-TOFMS (Agilent 6500 Series) operated in the negative (–) ion mode. 50 μL aliquots from the bubbler samples were directly injected onto the UPLC/ESI-HR-Q-TOFMS without additional treatment, and quantified with an authentic MAE standard. Details of UPLC/(–)ESI-HR-TOFMS operating conditions and procedures are described elsewhere (21). The detection limit of MAE by UPLC/(–)ESI-HR-TOFMS was 5 pg μL^{-1}, based on signal-to-noise ratios > 3:1, and the uncertainty was ~3%.

Reactive Uptake Studies Using MAE. Authentic MAE was synthesized according to procedures described in the *SI Text* and Fig. S6. The synthetic standard was characterized by NMR and UPLC/(–)ESI-HR-Q-TOFMS for confirmation of structure and purity (Fig. S7-S9). The purity of MAE was determined to be ~ 99%. Reactive uptake of MAE onto preexisting seed

aerosols was examined in the UNC 10-m^3 flexible Teflon indoor chamber. Details of this chamber have been described previously (11). A scanning electrical mobility sizing (SEMS) system (Brechtel Manufacturing Inc., Hayward, CA) equipped with a cylindrical-geometry differential mobility analyzer (DMA) and a mixing condensation particle counter (MCPC) was used to measure aerosol size distributions. Experiments were conducted with 300 ppbv MAE to ensure collection of sufficient SOA mass for off-line chemical analysis of reaction products. Aerosol samples were collected on Teflon membrane filters (Pall Life Science, 47 mm diameter, 1.0-µm pore size) at a sampling flow rate of ~ 20 L min^{-1} for 2 h. For each experiment, two Teflon filters were stacked in the filter holder. Front filters were collected to examine particle-phase reaction products. The back filters served to correct for absorption of gaseous MAE; however, no gaseous MAE was found to absorb. All experiments were carried out under dark and dry conditions (RH < 5%) at constant temperature (20–25°C). Control experiments, including clean chamber, MAE only, and seed aerosol (acidic and neutral seed) only, were performed to rule out artifacts. Filters collected from these experiments revealed no MAE-derived SOA constituents.

Theoretical Calculations. All GAUSSIAN 2009, NEB, DIMER and VARIFLEX calculations were run on an IBM iDataPlex cluster with six login nodes, with 160 compute nodes for running batch jobs, located in the National Computer Center on the U.S. EPA campus in Research Triangle Park, North Carolina. Each login node has two quad-core Intel Xeon x5550 processors and 48 GB of memory (6 GB/core), while each compute node has two quad-core Intel Xeon x5550 processors and either 32 GB or 48 GB of memory (4-6 GB/core). The Intel Xeon x5550 processors operate at 2.66 GHz. Details of our VARIFLEX calculations are described in the *SI Text*.

Ambient Gas and Fine Aerosol Collection and Analyses. Ambient gas samples were collected in Chapel Hill, NC, during summer 2012. The sampling site was located on the roof of the UNC Gillings School of Global Public Health building. Daytime (09:30-19:30, local time) and nighttime (20:30-06:30, local time) samples were collected. Samples were collected and analyzed in the same manner as gaseous samples collected from outdoor smog chamber studies, and quantified with an authentic MAE standard by UPLC/(–)ESI-HR-TOFMS. Archived ambient fine aerosol samples collected during the summer 2008 Mini-Intensive Gas and Aerosol Study (AMIGAS) in Atlanta, GA, at the Jefferson Street (JST) site were also analyzed. A detailed description of the sampling site and collocated measurements is provided elsewhere (45). Aerosol sample analysis is described in the *SI Text*.

Regional Chemical Transport Model Simulations. CMAQ Model v5.01 (46, 47) with the SAPRC07 chemical mechanism (48, 49) and isoprene updates (50) was further expanded to explicitly track peroxyacyl radicals from MACR oxidation, isoprene-derived MPAN, and later-generation MPAN oxidation products, including MAE and HMML to estimate ambient concentrations of MAE over the continental U. S. The yields and rate constant for the four MPAN product channels follow the yields estimated through computational chemistry in reaction [1]. See *SI Text* for additional documentation.

ACKNOWLEDGEMENTS. This research was supported in part by the National Institute of Environmental Health Sciences (P30ES010126). Y.-H.L. and J.D.S. were supported in part by the Electric Power Research Institute (EPRI). Y.-H.L. acknowledges a Dissertation Completion Fellowship from the UNC Graduate School. M.A. and S.H.B. were supported by the National Science Foundation Graduate Research Fellowship Program (NSF-GRFP) and Fulbright Presidential Fellowship Program, respectively. Richard Kamens, Elias Rosen, Glenn Walters,

and Denis Fedor are gratefully acknowledged for their assistance in the design and construction of the UNC indoor smog chamber. The authors thank Rodney Weber and Xiaolu Zhang for providing 2008 AMIGAS $PM_{2.5}$ filter samples. The authors also thank Bill Hutzell, Rob Pinder, Jose L. Jimenez, Joel Thornton, Douglas Worsnop, and Manjula Canagaratna for useful discussions. The U. S. Environmental Protection Agency through its Office of Research and Development collaborated in the research described here. It has been subjected to the Agency's administrative review and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

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Figure Legends

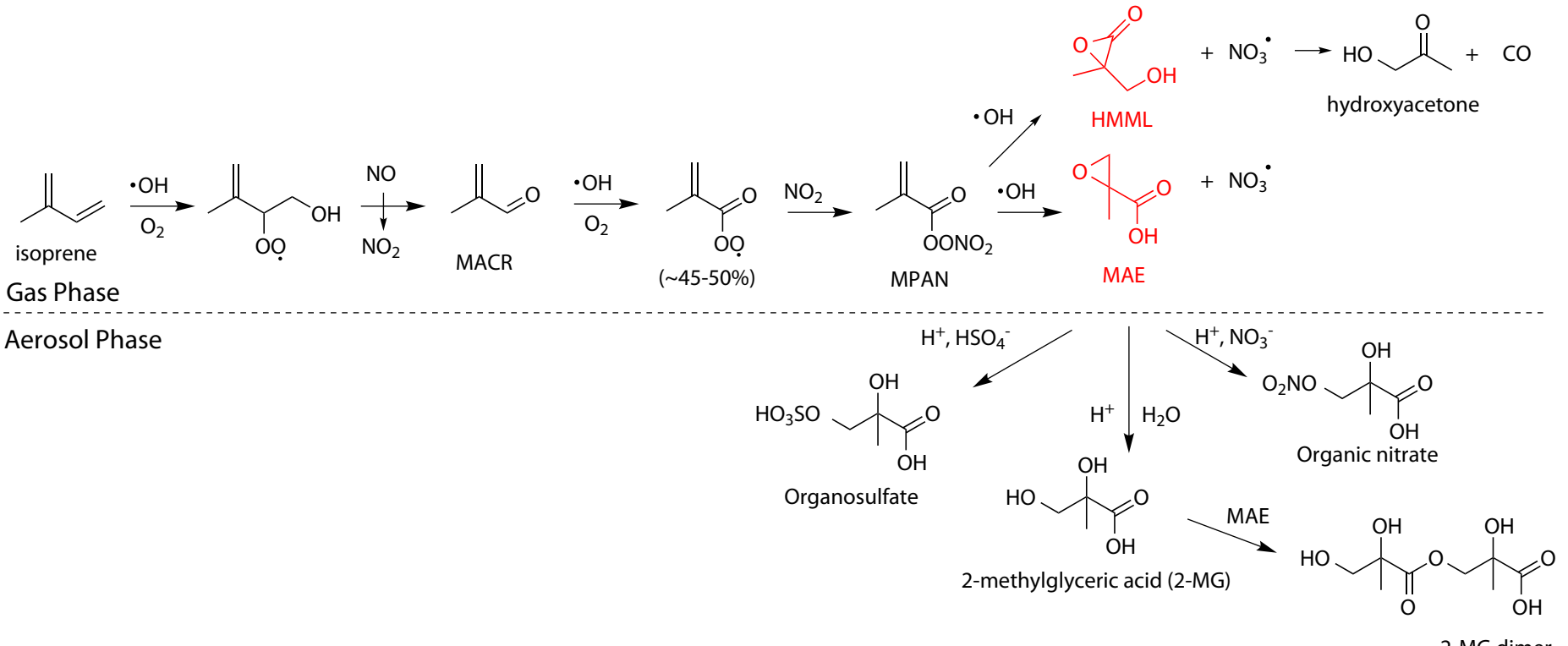
Fig. 1. Proposed mechanism for SOA formation from isoprene photooxidation in the presence of NO_x.

Fig. 2. Gaseous MAE detected by UPLC/(–)ESI-HR-Q-TOFMS from (A) an irradiated MACR/NO_x outdoor smog chamber experiment, (B) authentic MAE standard, and (C) an ambient air sample collected in Chapel Hill, NC, during summer 2012.

Fig. 3. GC/EI-MS traces and corresponding mass spectra showing the presence of 2-MG in aerosol collected from (A) an isoprene/NO_x photooxidation experiment, (B) an MACR/NO_x photooxidation experiment, (C) a dark reactive uptake study of MAE, and (D) an ambient $PM_{2.5}$ sample from downtown Atlanta, GA.

Fig. 4. Relative ZPE corrected energies (green) and product yields (orange) for the reaction of MPAN with OH calculated at m062x/ maug-cc-pvtz level of theory. Results are shown for the adjusted value of -2.80 kcal mol^{-1} for the TS_2 transition state energy.

Fig. 5. July 21 to August 20, 2006 (A) mean and (B) maximum surface layer MAE concentration over the continental U.S. simulated by the updated CMAQ model.


isoprene
•OH
O2
OH
OO
NO
NO2
MACR
•OH
O2
OO
(~45-50%)
NO2
OONO2
MPAN
•OH
•OH
HMML
+ NO3•
HO
+ CO
hydroxyacetone
MAE
+ NO3•
Gas Phase
Aerosol Phase
H+, HSO4-
HO3SO
Organosulfate
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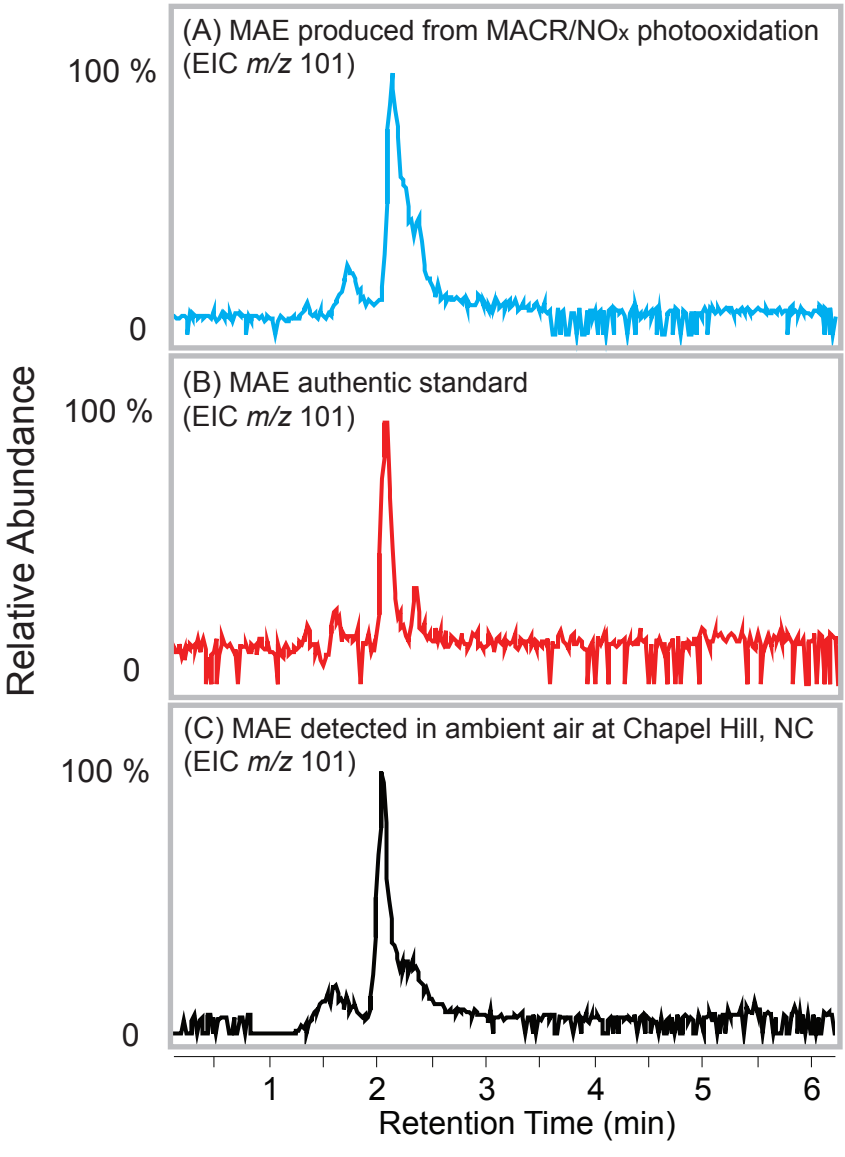
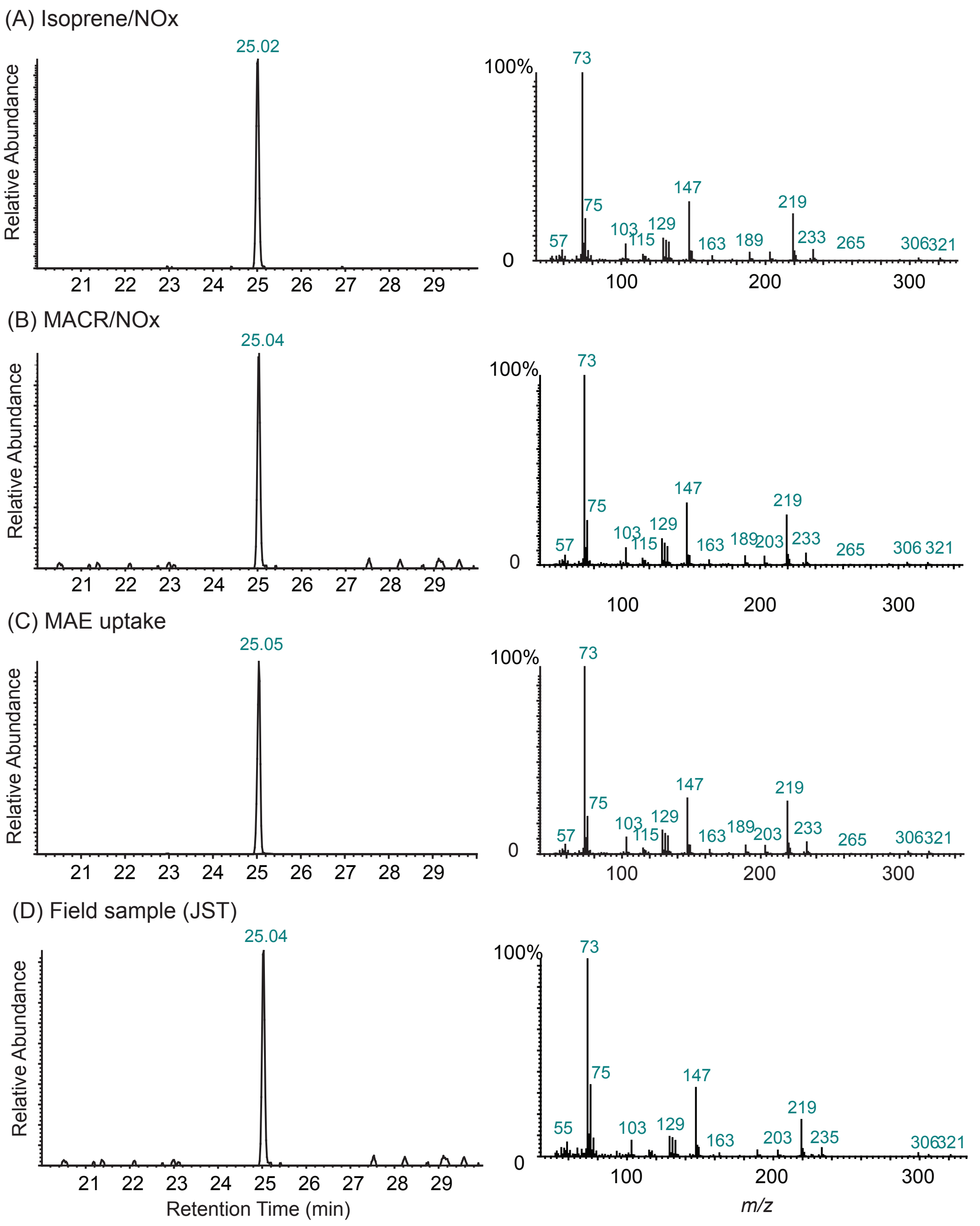
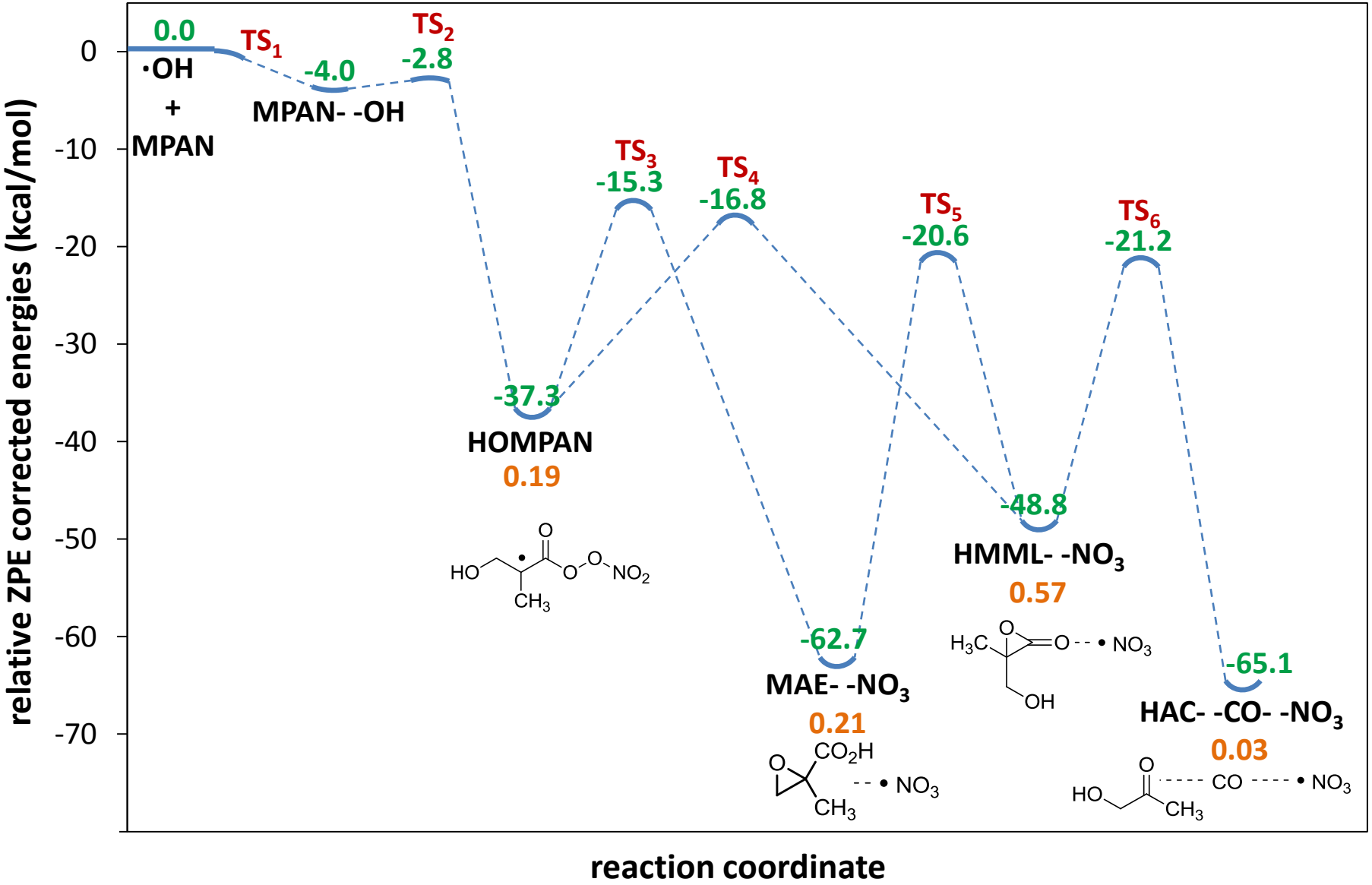
H+, NO3-
O2NO
Organic nitrate
MAE
2-MG dimer

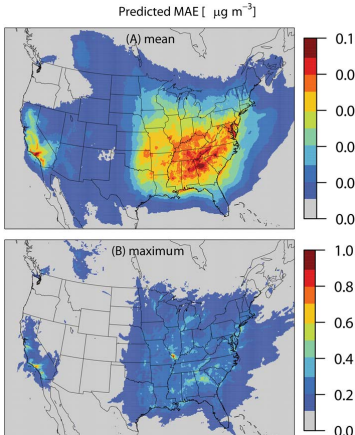

(A) MAE produced from MACR/NOx photooxidation
(EIC m/z 101)
100 %
0
(B) MAE authentic standard
(EIC m/z 101)
100 %
0
(C) MAE detected in ambient air at Chapel Hill, NC
(EIC m/z 101)
100 %
0
Relative Abundance
1
2
3
4
5
6
Retention Time (min)


(A) Isoprene/NOx
25.02
Relative Abundance
21 22 23 24 25 26 27 28 29
100%
0
73
75
57
103
115
129
147
163
189
219
233
265
306
321
100 200 300
(B) MACR/NOx
25.04
Relative Abundance
21 22 23 24 25 26 27 28 29
100%
0
73
75
57
103
115
129
147
163
189
203
219
233
265
306
321
100 200 300
(C) MAE uptake
25.05
Relative Abundance
21 22 23 24 25 26 27 28 29
100%
0
73
75
57
103
115
129
147
163
189
203
219
233
265
306
321
100 200 300
(D) Field sample (JST)
25.04
Relative Abundance
21 22 23 24 25 26 27 28 29
Retention Time (min)
100%
0
73
75
55
103
129
147
163
203
219
235
306
321
100 200 300
m/z

·OH + MPAN

k_{total} = 3.0 x 10^{-11} $cm^3 molecule^{-1} s^{-1}$ (T = 300 K, P = 760 Torr)




Predicted MAE [μg m-3]
(A) mean
0.10
0.08
0.06
0.04
0.02
0.00
(B) maximum
1.0
0.8
0.6
0.4
0.2
0.0