Contribution of isoprene to formaldehyde and ozone formation based on its oxidation products measurement in Beijing, China

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ABSTRACT

The atmospheric mixing ratios of methacrolein (MACR) and methyl vinyl ketone (MVK), the two specific products from isoprene oxidation in the atmosphere, were measured in Beijing from March to November, 2006. Distinct amounts of MACR and MVK were detected during vegetable growing seasons from April to October with ambient levels of 0.11–0.67 ppbv and 0.19–1.36 ppbv, respectively. The reacted isoprene and its ozone formation potentials (OFPs) in Beijing were evaluated in the range of 0.49–3.46 ppbv and 6.4–44.7 ppbv, respectively, from April to October. OFP of the reacted isoprene accounted for 10.6–23.6% of the total OFPs of VOCs (including carbonyls and isoprene) and 6.38–29.9% of the photo-chemically produced ozone. The maximum OFP of the original emitted isoprene prior to its photo-oxidation was calculated as 56.0 ppbv in August. The contribution from the reacted isoprene in Beijing to HCHO formation was also estimated to be in the range of 0.35–2.45 ppbv from April to October, which accounted for 4.6–11.5% of ambient HCHO.

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1. Introduction

Isoprene (C₅H₈) is the principal non-methane volatile organic compound (VOC) emitted from vegetation. Its global emission was estimated to be 500–750 Tg yr^{−1} (Guenther et al., 2006), which is several times higher than the anthropogenic VOCs emissions (100–200 Tg yr^{−1}) (Olivier and Berndowski, 2001), and typically more reactive than anthropogenic VOCs (Abelson, 1988). Researches conducted over the past decades have shown that isoprene contributes significantly to tropospheric ozone formation in rural (Trainer et al., 1987), suburban (Starn et al., 1998), and even urban areas (Chameides et al., 1988; Biesenthal and Shepson, 1997; Lee and Wang, 2006).

Recently, ozone formation potentials (OFPs) based on the observed atmospheric VOCs in a typical region were widely utilized to evaluate the reaction activity of the individual species to local atmospheric ozone formation (Wiedinmyer et al., 2001; Duane et al., 2002; Duan et al., 2008). However, the evaluation only based on the observed VOCs may result in underestimation, especially for

those species with high reactivity in the atmosphere (Song et al., 2007; Xie et al., 2008). Isoprene is just one of the most reactive VOCs, with atmospheric residual lifetime typically less than 1 h only respecting to the HO radical reaction during daytime (Trainer et al., 1987). Therefore, in addition to the observed ambient isoprene, isoprene consumed by photo-oxidation should be considered for OFPs evaluation. MVK and MACR are two specific products of isoprene photo-oxidation. The reacted isoprene can be quantified based on the observed MVK and MACR according to the approach developed by Atkinson (1997). Then, the more accurate OFP value for isoprene could be derived based on the observed isoprene plus the reacted isoprene.

During isoprene photo-oxidation process, formaldehyde (HCHO) can be produced in high yield (Finlayson-Pitts and Pitts, 1986). HCHO is considered as the major source for HO₂ free radical in the troposphere and also makes important contribution to ozone formation. Furthermore, HCHO is a toxic and carcinogenic air pollutant with potential or direct negative effects on human health. Recently, the contribution of atmospheric isoprene to HCHO has attracted many researchers' interest (Wiedinmyer et al., 2001; Duane et al., 2002; Mu et al., 2007).

The vegetation coverage in Beijing has significantly increased during past decades and the proportion of greening area was high up to 42.5% of total urban area in 2006 (Beijing Bureau of Statistics, 2007). The main species for greening are various broad-leaf

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deciduous trees, shrubbery, and lawn, and most of them are strong isoprene emitters, e.g. the dominant deciduous trees, *Platanus orientalis*, *Populus simonii*, and *Salix matsudana Koidz* (Zhang et al., 2000). The increased greening area will definitely lead to the significant increase of isoprene emission. Although vegetables are beneficial to human's living environments in many aspects, its adverse impacts should also be considered especially for photo-oxidants formation which will have significantly adverse influence on human health and eco-environment. It is well documented that the biogenic isoprene emission is affected by various factors including solar radiation, air temperature, leave age etc. and shows distinct seasonal variation (Duane et al., 2002; Guenther et al., 2006). Therefore, long-term field measurements in Beijing are necessary to investigate the contribution of isoprene to atmospheric ozone and HCHO.

In recent two studies conducted in Beijing urban area, both the reacted isoprene and the observed isoprene were considered to estimate the OFPs of isoprene (Song et al., 2007; Xie et al., 2008). The calculated OFP of isoprene accounted for 12.3% and 23% of the total OFPs for all VOCs in summer of 2005 (Song et al., 2007) and summer of 2006 (Xie et al., 2008), respectively. However, those studies were just based on a short-term (only one month) field measurements and the contribution of isoprene to HCHO formation was not investigated.

In this study, the mixing ratios of MACR and MVK in Beijing urban air were measured from March to November in 2006, and the reacted isoprene was subsequently calculated. The ozone and formaldehyde formation potentials of atmospheric isoprene were estimated.

2. Experimental

2.1. Site description

Beijing city (39.81N, 116.51E) is located in temperate zone with half-moist continent monsoon climate and four distinct seasons. Deciduous plants usually germinate at the end of March, flourish from April to September, and wither in the middle of October. In this study, field sampling was conducted from March to November 2006 on a rooftop (about 15 m above ground) in the Research Center for Eco-Environmental Sciences (RCEES), which is located between the north forth-ring road and the north fifth-ring road of Beijing and is a typical downtown site. The surroundings of RCEES are several institutes, campuses, residential apartments, and two side roads with moderate traffic. The RCEES is moderately covered by various plants,

including *P. orientalis*, *Pendula loud*, *P. simonii*, and *S. matsudana koidz*, etc., which is a representative site of Beijing dwelling district.

2.2. Carbonyls sampling and analysis

The whole sampling campaign was conducted from March to November 2006. Air samples were usually collected from 08:00 a.m. to 20:00 p.m. (LT, Beijing time) in the days with sunny and stable weather condition. The sampling days for each month were 5 days for March, 7 days for April, 3 days for May, September and December, respectively; 4 days for June, July, and October, respectively; 6 days in August.

The carbonyls sampling and analysis were based on the EPA TO-11A method (EPA, 1999). The detailed information about the atmospheric carbonyls sampling and analysis was described in our previous works (Pang and Mu, 2006; Mu et al., 2007). Ground-level ozone and NO₂ were measured using an ozone analyzer (TE, Model 49) and a NO–NO₂ analyzer (Monitor Labs ML9830 Series). Photo-synthetically active radiation (PAR) was measured with a LI-COR quantum sensor (LICOR, Lincoln, NE, USA).

3. Results and discussion

Ten species of carbonyl compounds were identified in the ambient air of Beijing in this study including methyl vinyl ketone (MVK), mathacrolein (MACR), formaldehyde (Form), acetaldehyde (Acet), acetone, propionaldehyde (Propin), butyraldehyde (Butyr), hexaldehyde (Hex), valeraldehyde (Valer), and benzaldehyde (Benz). MVK, MACR and formaldehyde will be primarily discussed in the following sections.

3.1. Diurnal variations of MVK, MACR and HCHO

MVK and MACR were detected in 134 samples among 208 samples with their concentrations in the ranges of 0.12–2.36 and 0–1.25 ppbv, respectively. HCHO was found in all samples with its range of 1.6–52.0 ppbv. Diurnal variations of MVK, MACR, and HCHO for each month were shown in Figs. 1 and 2, respectively. The peak concentrations of MVK and MACR in diurnal profiles usually appeared in the period from 10:00 a.m. to 16:00 p.m., which was in accordance with the period of daily peak emission of isoprene from deciduous trees in Beijing (Zhang et al., 2000), indicating that MVK and MACR in Beijing ambient air were predominantly produced from photo-oxidation of biogenic isoprene. Although MVK, MACR

Fig. 1. Average diurnal variations of MVK (left plot) and MACR (right plot) during sampling months.

Fig. 2. Average diurnal variations of atmospheric HCHO concentrations during sampling months.

and isoprene had been even detected in vehicular emission (Biesenthal and Shepson, 1997), the atmospheric MVK and MACR were under the detection limits in March and November, and in most of evening time (during 18:00–20:00 h in April, September and October) in this study, implying that the anthropogenic contribution to MVK, MACR and isoprene might be negligible. In March and November, most deciduous trees around Beijing are in the periods of leaf emergence and leaf senescence, respectively, when biogenic sources were inactive and their isoprene emissions were quite weak (Steinbrecher et al., 1997; Zhang et al., 2000). So it is easy to understand why atmospheric MVK and MACR in Beijing were not detected until the later period of April, when the leaves of broad-leaf trees grow to their full expansions. The low concentrations of MVK and MACR in the evening may be also ascribed to the weak isoprene emission due to the low or no solar radiation (Lee and Wang, 2006). Fig. 3 is the diurnal profiles of MVK, MACR, air temperature, PAR, and ozone during the typical summer days (15–16 August, 2006). The similar trends among MVK, MACR, air temperature, PAR, and ozone further indicated MVK and MACR were mainly from biogenic isoprene photo-oxidation and elevated by the increasing air temperature and PAR.

During the whole sampling period, the concentration of MVK was significantly higher than that of MACR with the MVK/MACR ratios varying from 1.01 to 2.8 (Fig. 4). The MVK/MACR ratios were found to be usually maximum at noon and minimum in evening or morning. Similar phenomenon was also reported by Stroud et al. (2001) who observed the maximum ratio (2.0) in the early afternoon and minimum ratio (1.1) in night. In daytime, the photo-oxidation of isoprene was dominated by the reaction with HO radical as shown in equation (1) with the yield ratio for MVK/MACR of 1.5 (Atkinson, 1997). Additionally, as equation (2) and (3) shown, MACR can be lost faster than MVK in daytime by HO-initiated oxidation (Chuong and Stevens, 2004). So, a ratio exceeding 1.5 would be expected during daytime.

In the morning and evening, isoprene ozonolysis dominates over HO-initiated oxidation and the yields of MVK and MACR were

0.17 and 0.44 from isoprene ozonolysis (Warneke et al., 2004). Furthermore, MVK reacts faster with ozone than MACR (Yokouchi, 1994). In evening, the NO_3 reaction can also cause rapid consumption of isoprene, while producing small amounts of MVK and MACR with their yields of 3.5% (Kwok et al., 1996). So a low ratio would be expected from the ozonolysis reactions in the evening and morning.

HCHO was detected throughout the sampling period and found as the most abundant carbonyl compound in this study. As shown in Fig. 2, HCHO concentrations were low (about 6 ppbv) with little

Fig. 3. Typical diurnal variations for MVK, MACR, HCHO, ozone, air temperature and PAR in typical summer days (15–16 August 2006).

Fig. 4. Regression of MVK vs MACR during the whole sampling period.

variation in the diurnal patterns in March and December. In July and August, HCHO concentration was extremely elevated (up to 30 ppbv) and showed distinct diurnal variation due to significant contribution of photo-oxidation of VOCs to ambient HCHO (Pang and Mu, 2006). Assuming that HCHO in March totally come from direct anthropogenic emission, and the strength of this direct emission was identical to those in other seasons, and the influence of meteorological conditions was neglected, the contributions from VOCs photo-oxidation to HCHO in Beijing could be roughly estimated from the data in Fig. 2 and account for 71%, 78% and 73% of total HCHO in June, July and August, respectively.

3.2. Contribution of isoprene to HCHO and ozone formation potential

In order to assess the relative importance of sources (biogenic versus anthropogenic) to atmospheric HCHO, an attempt was done to estimate the concentration of HCHO attributed to isoprene photo-oxidation ($[\text{HCHO}]_{\text{isoprene}}$). Assuming that the observed MACR and MVK in Beijing ambient air are absolutely derived from the isoprene oxidation by HO radical with their yields of 0.23 and 0.32, respectively, the consumption of the reacted isoprene ($\Delta\text{isoprene}$) can be roughly estimated based on the measured MACR and MVK concentrations according to the following equation (4). This approach was commonly employed by numerous studies (Stroud et al., 2001; Duane et al., 2002; Mu et al., 2007).

$$\Delta\text{isoprene} = 0.5[\text{MACR}]/0.23 + 0.5[\text{MVK}]/0.32 \quad (4)$$

Then, $[\text{HCHO}]_{\text{isoprene}}$ can be calculated from the reacted isoprene according to the following equation (5)

$$[\text{HCHO}]_{\text{isoprene}} = f\Delta\text{isoprene} (f = 0.63) \quad (5)$$

where f is the total fractional yield of HCHO from isoprene oxidation (Carter and Atkinson, 1996). The amounts of HCHO derived from isoprene photo-oxidation for all samples were calculated and listed in Table 1. The maximum amount of HCHO from isoprene photo-oxidation was 6.0 ppbv in the noon of 8 August 2006. As shown in Table 1, the monthly average concentrations and the proportions of HCHO produced from isoprene oxidation varied over 0.35–2.53 ppbv and 4.64–11.45%, respectively, with peak values in August. These results indicated that the isoprene oxidation to atmospheric HCHO in Beijing cannot be neglected. It must be noted that the above approach is based on the crude assumption that the photochemical lifetime of MACR and MVK is much longer than that of isoprene (Carter and Atkinson, 1996; Atkinson, 1997). Although the reactions of MACR and MVK with HO are much slower than that of isoprene, the fast photolysis rates of MACR and MVK in summer midday should be considered, and the approach may underestimate the contribution of isoprene to HCHO under this condition.

To distinguish the contribution of individual VOC to ambient ozone is very important for efficiently control measure in the urban areas where ozone formation is VOC-sensitive. In most urban areas including Beijing, the ozone formation has been recognized to be controlled by VOCs due to plenty of NO_x in the ambient air (Xie et al., 2008; Song et al., 2007; Xu et al., 2006). The ozone formation potential (OFP), which is the product of the mixing ratio of VOC species and the maximum incremental reactivity (MIR) as developed by Carter (1994), is a widely used method for evaluating the maximum ozone formation capacity of each VOC and adopted in this study. As shown in Table 2, the OFPs of eight dominant carbonyls were calculated based on their monthly average concentrations and their MIR. Total OFPs of those carbonyls varied from 42.2 to 144.3 ppbv. Formaldehyde was found as the predominant contributor to the OFPs with values of 24.7–99.2 ppbv. The same finding in Beijing was also reported in the study of Duan et al. (2008).

The OFPs values derived by the observed VOC must be great underestimated for those (such as isoprene) with high reactivity in the atmosphere. Xie et al. (2008) found that the OFPs values for the total VOCs observed by them increased by 70% after considering the consumed VOCs via OH reaction during daytime. Lee and Wang (2006) also pointed out that the loss profile of a precursor is of greater interest to assess the impact on ozone formation, and they simulated the loss profile of isoprene under two scenarios based on the first order reaction of isoprene with OH, and found the reacted

Table 1

Mixing ratios of HCHO (ppbv) derived from the reacted isoprene, isoprene contribution accounted for total ambient HCHO (%) and the OFP of ambient HCHO.

Month	08:00–10:00	10:00–12:00	12:00–14:00	14:00–16:00	16:00–18:00	18:00–20:00	Monthly average	Ambient HCHO	Isoprene contribution
	Mean $\pm$ SD	Mean $\pm$ SD	Mean $\pm$ SD	Mean $\pm$ SD	Mean $\pm$ SD	Mean $\pm$ SD			
Mar.	ND ^a	ND	ND	ND	ND	ND	ND	5.51	0%
April	0.88 $\pm$ 0.01	0.80 $\pm$ 0.49	0.75 $\pm$ 0.28	0.72 $\pm$ 0.20	0.48 $\pm$ 0.39	ND	0.73 $\pm$ 0.35	10.55	6.89%
May	0.88 $\pm$ 0.02	1.21 $\pm$ 0.32	1.11 $\pm$ 0.08	0.75 $\pm$ 0.13	0.72 $\pm$ 0.14	0.59 $\pm$ 0.12	0.88 $\pm$ 0.14	10.78	8.14%
June	0.77 $\pm$ 0.13	1.18 $\pm$ 0.40	1.34 $\pm$ 0.78	1.36 $\pm$ 0.64	0.98 $\pm$ 0.19	0.93 $\pm$ 0.21	1.09 $\pm$ 0.42	9.815	11.17%
July	1.58 $\pm$ 0.48	2.39 $\pm$ 0.82	2.55 $\pm$ 1.17	1.92 $\pm$ 0.74	1.61 $\pm$ 0.53	1.27 $\pm$ 0.36	1.88 $\pm$ 1.04	19.90	9.48%
Aug.	1.21 $\pm$ 0.24	3.54 $\pm$ 1.05	2.79 $\pm$ 0.84	2.19 $\pm$ 0.47	1.78 $\pm$ 0.31	1.26 $\pm$ 0.66	2.53 $\pm$ 0.74	22.04	11.45%
Sep.	0.59 $\pm$ 0.28	0.40 $\pm$ 0.09	0.50 $\pm$ 0.22	0.23 $\pm$ 0.19	0.17 $\pm$ 0.17	ND	0.38 $\pm$ 0.12	5.49	6.88%
Oct.	0.29 $\pm$ 0.12	0.44 $\pm$ 0.04	0.34 $\pm$ 0.11	0.33 $\pm$ 0.13	0.33 $\pm$ 0.13	ND	0.35 $\pm$ 0.15	7.49	4.64%
Nov.	ND	ND	ND	ND	ND	ND	ND	4.46	0%

^a Not detected.

Table 2

OFP (ppbv) of ambient each carbonyl compound during the sampling period.

Carbonyls	Form	Acet	Acetone	Propion	Butyr	Hex	Valer	Benz	Total
Mar.	24.8	6.2	0.89	6.9	1.65	1.01	1.18	−0.42	42.21
April	47.5	7.5	2.0	7.6	2.14	1.19	1.38	−0.44	68.86
May	48.5	12.3	2.87	8.4	2.78	1.82	2.12	−0.54	78.26
June	44.3	17.7	2.61	10.6	3.57	2.03	2.37	−0.57	82.61
July	89.4	20	5.49	11.8	4.1	2.23	2.6	−0.87	134.7
Aug.	99.2	21.3	1.88	13.0	4.33	2.41	2.81	−0.63	144.3
Sep.	24.7	11.5	2.14	11.1	3.0	1.77	2.06	−0.5	55.77
Oct.	33.7	8.9	1.46	9.7	2.09	0.97	1.13	−0.41	57.54
Nov.	20.1	8.4	1.36	7.8	1.55	0.76	0.89	−0.38	40.48

isoprene is about 2.6-fold of the observed isoprene for the noon-time peak value. Xie et al. (2008) calculated the initial isoprene mixing ratio based on the observed atmospheric isoprene, MVK and MACR and the first order reactions of isoprene, MVK and MACR with OH. Both methods of Lee and Wang (2006) and Xie et al. (2008) provided important evidence that the consumed isoprene makes great contribution to ozone formation. However, the consumed isoprene calculated by the two methods can only represent the approximate value, because the reactions of isoprene, MVK and MACR with OH are not strictly according to the first order law in the actual atmospheric environment due to significant variations of isoprene emission and OH concentration. In addition, the value of $OH_{avg}t$ derived from the observed ratios of MVK to isoprene or MACR to isoprene by Xie et al. (2008) must be largely underestimated due to continuously isoprene emission from vegetables, and hence underestimated the consumed isoprene. In this study, the reacted isoprene was simply calculated according to the equation (4) based on the measured MACR and MVK. It should be mentioned that the reacted isoprene calculated by this study only represents the lower limit because the loss of MACR and MVK in the atmosphere were not considered. In Table 3, the monthly average concentrations of the reacted isoprene were estimated to be in range of 0.49–3.46 ppbv. The OFPs of the reacted isoprene were calculated in the range of 6.4–44.7 ppbv with maximum in August, which accounted for 10.6–23.5% of the total OFPs of the measured VOCs including carbonyls and isoprene, and 6.4–29.9% photo-chemically produced ozone (the observed ambient O_3 and NO_2).

Xie et al. (2008) reported the average mixing ratio of the atmospheric isoprene at Peking university site was 0.89 ± 0.55 ppbv during August and September 2006. Assuming that the average mixing ratio of atmospheric isoprene in August was identical to the average level (0.89 ppbv) at our sampling site, the total concentration of isoprene including the reacted isoprene and the atmospheric isoprene in August can be obtained as 4.34 ppbv and its OFP can be estimated as 56.0 ppbv which was about 40% higher than the value of OFP (42 ppbv) estimated by Xie et al. (2008). As mentioned above, the OFP value estimated by Xie et al. (2008) may be largely underestimated due to continually

Table 4

Comparison of HCHO, MVK, MACR and isoprene in various cities during summer time (ppbv).

Cities	Sampling Time	HCHO	MVK	MACR	Isoprene	Refer.
Beijing, (urban)	Aug–Sep., 2006	– ^a	0.34	0.70	0.89	Xie et al., 2008
Beijing, (rural)		–	0.37	0.55	0.64	Xie et al., 2008
Beijing	Aug., 2006	26.82	–	–	1.17	Duan et al., 2008
Zürich (Switzerland)	Summer	2.35	0.08	0.04	0.16	Legreid et al., 2007
Insubria, Italy	Aug., 2000	4.0	~5.0	~2.8	20	Duane et al., 2002
Nashville, USA	June–July, 1999	–	0.43	0.24	0.41	Stroud et al., 2001
Austin, USA (urban)	Aug., 1998	0.4–3.2	–	0.2–5.7	0.3–6.0	Wiedinmyer et al., 2001
Austin, USA (rural)		0.4–20	–	0.1–3.7	0.3–10.2	
Vancouver, Canada	Aug., 1993	–	2.0	1.0	5.3	Biesenthal et al., 1997
Kinterbish, USA	June–July, 1990	–	0.98	0.66	–	Montzka et al., 1993
Beijing	Aug., 2006	22.04	1.36	0.67	–	This study

^a No reported data.

isoprene emission from vegetables. In addition, the temporal and spatial difference between the two measurements may also account for the discrepancy. Finally, the average mixing ratios of MACR (0.7 ± 0.42 ppb) and MVK (0.34 ± 0.17 ppb) obtained by Xie et al. (2008) are contrary to the stoichiometric reaction of OH with isoprene as well as the different reactivity of MACR and MVK.

3.3. Comparison of HCHO, MVK, MACR and isoprene in other cities

As Table 4 shows, the atmospheric HCHO in Beijing city in August measured by this study is in good agreement with that of Duane et al. (2002), and significantly higher than those of other cities, indicating that the great amount of vehicular exhaust from millions of vehicles in Beijing city may be responsible. The MVK and MACR of Beijing are comparable with those of Nashville (Stroud et al., 2001) and Kinterbish (Montzka et al., 1993) but lower than those of cities surrounded by forest such as Insubria (Duane et al., 2002), Vancouver (Biesenthal et al., 1997) and Austin (Wiedinmyer et al., 2001). The atmospheric isoprene of Beijing is a few higher than those of a forest site in Nashville and an urban background site in Zürich (Legreid et al., 2007), which implies that the isoprene from biogenic source in Beijing is significant. The highest concentration of MVK, MACR and isoprene were reported in the Insubria of Italy, in which the isoprene's contribution to the local ozone formation was calculated to be as high as 50–75% in summer (Duane et al., 2002).

Table 3

Estimated OFP (ppbv) and maximum contributions of reacted isoprene to total OFP (%) and photo-chemically produced ozone on monthly average value.

Month	Observed MACR	Observed MVK	Reacted isoprene	OFP of reacted isoprene	OFP of VOCs ^a	Contribution to OFP	Photo-chemically produced O_3	Contribution to photo-chemically produced O_3
April	0.18	0.27	0.79	10.2	79.06	12.9%	68	15.0 %
May	0.27	0.40	1.18	15.3	93.55	16.4%	99.3	15.4%
June	0.33	0.52	1.49	19.2	101.8	18.9%	91.0	21.1 %
July	0.54	1.03	2.69	34.8	169.5	20.5%	144.7	24.1 %
Aug.	0.67	1.36	3.46	44.7	188.9	23.6%	149.1	29.9%
Sep.	0.12	0.19	0.49	7.0	62.77	11.1%	109.7	6.38 %
Oct.	0.11	0.20	0.52	6.8	64.34	10.6%	53.0	12.8 %

^a VOCs includes carbonyls and isoprene.

4. Conclusion

In this study, the contributions of biogenic isoprene to ozone and HCHO in Beijing ambient air were estimated. The maximum ozone formation capacity for atmospheric isoprene in August was calculated to be 56.0 ppbv and accounted for 37.5% of the photochemically produced ozone. The amounts of HCHO attributed to the reacted isoprene varied in the range of 0.35–2.53 ppbv from April to October, which accounted for the 4.64–11.45% of total ambient HCHO. It is evident that the contribution of biogenic isoprene in Beijing to local photo-oxidant formation is significant, especially during summer time. The estimations in this study provided useful information to the policy-maker of Beijing municipal government that the influence of biogenic isoprene should be considered in order to develop an effective control strategy for ground-level ozone abatement.

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