Supplement of

Source apportionment and environmental impacts of anthropogenic VOCs in Lhasa, a highland city in China

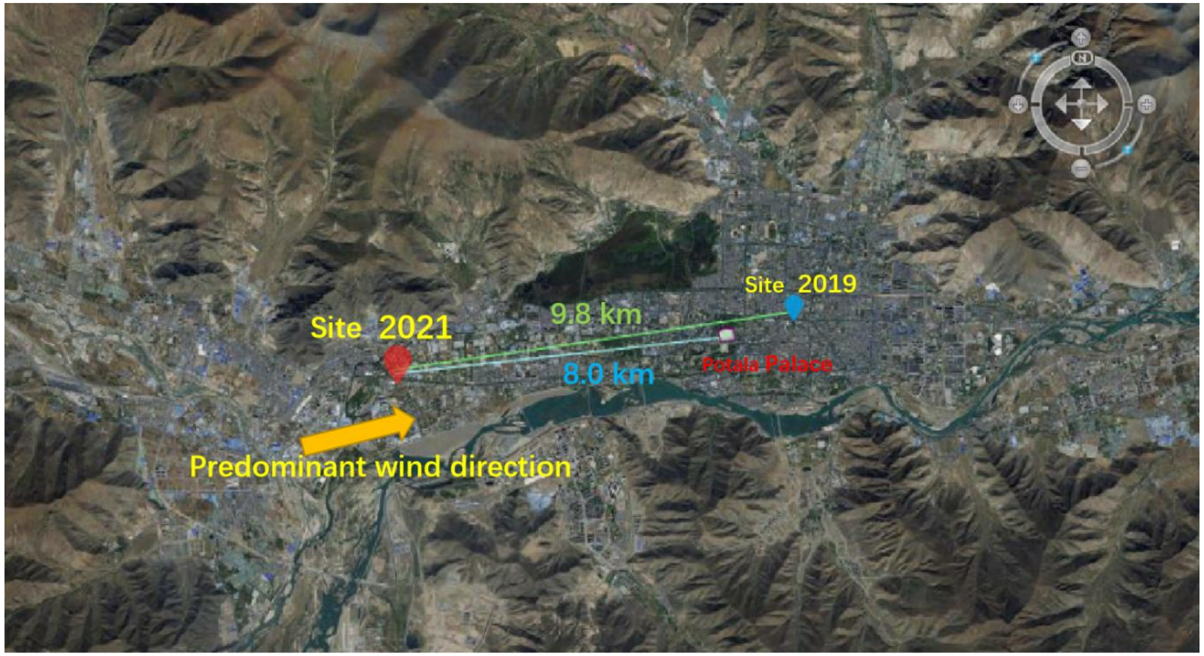

Figure S1. Measurement location in the west corner of the Lhasa city and its relative position to our previous measurement. The site map is available via:https://zhfw.tianditu.gov.cn/.

Table S1 Concentration, standard deviation and sources of measured VOC species

Class	Species	Mean/ppb	STD	Species Number	S/N	Sources	References
Alkyne	Acetylene	0.299	0.182	1	2.33	Biomass burning, Coal burning, Vehicle emissions	(Liu et al., 2008)
Nitrile	Acetonitrile	1.112	1.429	2	2.00	Biomass burning	(Chen et al., 2017)
Alkane	Ethane	0.780	0.192	3	2.33	Combustion, Vehicle emissions	(Stein and Rudolph, 2007)
	Propane	1.283	1.748	4	2.33	Combustion，NG/LPG	(Liu et al., 2008)
	Isobutane	0.485	0.578	5	2.33	Vehicle emissions	(Baudic et al., 2016)
	n-Butane	0.558	0.726	6	2.33	Vehicle emissions	(Baudic et al., 2016)
	Isopentane	0.314	0.455	7	2.30	Gasoline evaporation，Vehicle emissions	(Liu et al., 2008)
	n-Pentane	0.127	0.132	8	2.28	Gasoline evaporation，Vehicle emissions	(Liu et al., 2008)
	Cyclopentane	0.002	0.011				
	2,2-Dimethylbutane	0.009	0.008				
	2,3-Dimethylbutane	0.088	0.177				
	2-Methylpentane	0.034	0.069				
	3-methylpentane	0.044	0.062				
	n-Hexane	0.050	0.040				
	2,4-Dimethylpentane	0.009	0.007				
	Methylcyclopentane	0.016	0.022				
	2-Methylhexane	0.016	0.018				
	Cyclohexane	0.008	0.006				
	2,3-Dimethylpentane	0.006	0.009				
	3-Methylhexane	0.020	0.021				
	2,2,4-Trimethylpentane	0.014	0.013				
	n-Heptane	0.039	0.029				
	Methylcyclohexane	0.006	0.008				
	2,3,4-Trimethylpentane	0.004	0.004				
	2-methylheptane	0.007	0.006				
	3-Methylheptane	0.006	0.006				
	Octane	0.034	0.030				
	n-Nonane	0.022	0.017				
	n-Decane	0.012	0.007				
	Undecane	0.050	0.146				

Class	Species	Mean/ppb	STD	Species Number	S/N	Sources	References
Alkene	Ethylene	0.405	0.273	9	2.32	Combustion, Biogenic	(Baudic et al., 2016) (Goldstein et al., 1996)
	Propene	0.219	0.191	10	2.31	Combustion, Biogenic	(Wang et al., 2009) (Sindelarova et al., 2014)
	trans-2-Butene	0.029	0.076	11	0.75	Vehicle emissions	(Liu et al., 2008)
	1-Butene	0.068	0.070	12	2.00	Vehicle emissions	(Liu et al., 2008)
	1,3-Butadiene	0.073	0.100	13	2.01	Vehicle emissions, Biomass burning	(Liu et al., 2008)
	1-Pentene	0.037	0.033	14	1.76	Vehicle emissions	(Liu et al., 2008)
	trans-2-Pentene	0.016	0.026	15	1.03	Vehicle emissions	(Liu et al., 2008)
	Isoprene	0.175	0.255	16	2.01	Biogenic sources	(Sindelarova et al., 2014)
	cis-2-Butene	0.005	0.032				
	cis-2-Pentene	0.021	0.034				
	1-Hexene	0.038	0.033				
Aromatic	Benzene	0.086	0.061	17	2.30	Biomass burning, Vehicle emissions, Industrial	(Liu et al., 2008)
	Toluene	0.278	0.526	18	2.32	Solvent, Biomass burning, Vehicle emissions, Industrial	(Liu et al., 2008)
	Ethylbenzene	0.075	0.076	19	2.26	Solvent, Biomass burning, Vehicle emissions, Industrial	(Liu et al., 2008)
	m/p-Xylene	0.156	0.146	20	2.31	Solvent, Biomass burning, Vehicle emissions, Industrial	(Liu et al., 2008)
	o-Xylene	0.158	0.143	21	2.31	Solvent, Biomass burning, Vehicle emissions, Industrial	(Liu et al., 2008)
	Styrene	0.029	0.024	22	2.10	Solvent, Vehicle emissions, Industrial	(Yuan et al., 2010)
	n-Propylbenzene	0.005	0.004	23	0.29	Solvent	(Yuan et al., 2010)
	3-Ethyltoluene	0.013	0.014	24	1.23	Solvent	(Yuan et al., 2010)
	4-Ethyltoluene	0.007	0.007	25	0.52	Solvent	(Yuan et al., 2010)
	1,3,5-Trimethylbenzene	0.007	0.007	26	0.51	Solvent	(Yuan et al., 2010)
	2-Ethyltoluene	0.006	0.006	27	0.43	Solvent	(Yuan et al., 2010)
	1,2,4-Trimethylbenzene	0.017	0.021	28	1.47	Solvent	(Yuan et al., 2010)
	Isopropylbenzene	0.003	0.003				
	1,2,3-Trimethylbenzene	0.005	0.005				
	1,3-Diethylbenzene	0.001	0.001				
	1,4-Diethylbenzene	0.003	0.003				

Class	Species	Mean/ppb	STD	Species Number	S/N	Sources	References
Halohydrocarbon	Chloromethane	0.900	0.164	29	2.33	Biomass burning	(Liu et al., 2008)
	Freon11(CCl3F)	0.321	0.016	30	2.33	Background compounds	(Saeaw and Thepanondh, 2015)
	Dichloromethane	0.273	0.215	31	2.33	Solvent, Industrial	(Huang et al., 2014)
	Chloroform	0.040	0.030	32	2.23	Industrial solvents or additives	(Cai et al., 2010)
	1,2-Dichloroethane	0.084	0.074	33	2.28	Industrial solvents or additives	(Cai et al., 2010)
	Freon114(C2Cl2F4)	0.028	0.003				
	Vinyl chloride	0.009	0.018				
	Bromomethane	0.003	0.002				
	Chloroethane	0.005	0.007				
	1,1-Dichloroethylene	0.001	0.001				
	Freon113(C2Cl3F3)	0.098	0.004				
	1,1-Dichloroethane	0.050	0.129				
	cis-1,2-Dichloroethylene	0.001	0.002				
	1,1,1-Trichloroethane	0.003	0.001				
	Tetrachloromethane	0.110	0.008				
	Trichloroethylene	0.002	0.007				
	1,2-Dichloropropane	0.038	0.049				
	Bromodichloromethane	0.002	0.001				
	trans-1,3-Dichloropropene	0.002	0.003				
	cis-1,3-Dichloropropene	0.000	0.000				
	1,1,2-Trichloroethane	0.010	0.014				
	Tetrachloroethylene	0.010	0.019				
	1,2-Dibromoethane	0.000	0.001				
	Chlorobenzene	0.002	0.002				
	1,3-Dichlorobenzene	0.002	0.001				
	1,4-Dichlorobenzene	0.002	0.001				
	Benzylchloride	0.001	0.001				
	1,2-Dichlorobenzene	0.001	0.001				

Class	Species	Mean/ppb	STD	Species Number	S/N	Sources	References
OVOC	Acetaldehyde	3.591	3.441	34	2.33	Combustion, Vehicle emissions, Second formation	(Baudic et al., 2016)
	Acrolein	0.247	0.154	35	2.31	Vehicle emissions, Cooking, Second formation	(Sha et al., 2021)
	Propanal	0.717	0.508	36	2.33	Biomass burning, Second formation	(Zhang et al., 2013)
	Acetone	2.530	0.834	37	2.33	Solvent, Combustion, Second formation	(Sha et al., 2021)
	Methyl Tert-Butyl Ether	0.099	0.164	38	2.22	Gasoline vehicle emissions	(Zhang et al., 2013)
	Methacrolein	0.078	0.060	39	2.27	Biogenic sources	(Guenther et al., 2012)
	n-Butanal	0.512	0.379	40	2.33	Second formation	(Liu et al., 2009)
	Methyl Vinyl Ketone	0.190	0.119	41	2.32	Biogenic sources	(Guenther et al., 2012)
	Methyl Ethyl Ketone	0.346	0.186	42	2.33	Second formation	(Mellouki et al., 2015)
	2-Pentanone	0.067	0.056	43	2.17	Second formation	(Mellouki et al., 2015)
	n-Pentanal	0.453	0.474	44	2.32		
	3-Pentanone	0.040	0.040	45	2.00		
	n-Hexanal	0.465	0.505	46	2.33		
Inorganic	BC（ug/m^3)	0.8	0.6	47	2.98	Biomass burning, Diesel vehicle emissions	(Gentner et al., 2017)
	NOx	5.00	5.38	48	2.33	Combustion, Vehicle emissions (especially diesel vehicle)	(Gentner et al., 2017)
	NO	3.98	4.53	49	2.33	Combustion, Vehicle emissions (especially diesel vehicle)	(Gentner et al., 2017)
	CO (ppm)	0.138	0.035	50	3.50	Combustion, Vehicle emissions	(Gentner et al., 2017)
	O_3	49.6	12.9				

Table S2 Comparison of various VOCs concentrations with other observed results in Lhasa (ppb)

Period	Latitude	Longitude	Species	TVOCs	Alkanes	Alkenes	Aromatics	OVOC	Halohydrocarbons	Others
1998.6[a]	29.67	91. 13	69	113.5	24.2	22.9	55.0	-	-	11.4
2019[b]	29.65	91. 14	107	49.8	30.5	4.5	2.5	5.8	4.5	2.1
2019.05[c]	29.65	91.13	55	21.5	12.4	4.5	4.6	-	-	-
2021.5-6[*]	29.63	91.02	98	18.7	4.0	1.1	0.9	9.3	2.0	1.4

a.(Yu et al., 2001), b.(Yu et al., 2022), c.(Guo et al., 2022), * This study.

References:

Baudic, A., Gros, V., Sauvage, S., Locoge, N., Sanchez, O., Sarda-Esteve, R., Kalogridis, C., Petit, J.-E., Bonnaire, N., Baisnee, D., Favez, O., Albinet, A., Sciare, J., and Bonsang, B.: Seasonal variability and source apportionment of volatile organic compounds (VOCs) in the Paris megacity (France), A Atmos. Chem. Phys., 16, 11961–11989, https://doi.org/10.5194/acp-16-11961-2016, 2016.

Cai, C., Geng, F., Tie, X., Yu, Q., and An, J.: Characteristics and source apportionment of VOCs measured in Shanghai, China, Atmos. Environ., 44, 5005–5014, https://doi.org/10.1016/j.atmosenv.2010.07.059, 2010.

Chen, J., Li, C., Ristovski, Z., Milic, A., Gu, Y., Islam, M. S., Wang, S., Hao, J., Zhang, H., He, C., Guo, H., Fu, H., Miljevic, B., Morawska, L., Thai, P., Lam, Y. F., Pereira, G., Ding, A., Huang, X., and Dumka, U. C.: A review of biomass burning: Emissions and impacts on air quality, health and climate in China, Sci Total Environ., 579, 1000–1034, https://doi.org/10.1016/j.scitotenv.2016.11.025, 2017.

Gentner, D. R., Jathar, S. H., Gordon, T. D., Bahreini, R., Day, D. A., El Haddad, I., Hayes, P. L., Pieber, S. M., Platt, S. M., de Gouw, J., Goldstein, A. H., Harley, R. A., Jimenez, J. L., Prevot, A. S. H., and Robinson, A. L.: Review of Urban Secondary Organic Aerosol Formation from Gasoline and Diesel Motor Vehicle Emissions, Environ. Sci. Technol., 51, 1074–1093, https://doi.org/10.1021/acs.est.6b04509, 2017.

Goldstein, A. H., Fan, S. M., Goulden, M. L., Munger, J. W., and Wofsy, S. C.: Emissions of ethene, propene, and 1-butene by a midlatitude forest, J. Geophys. Res.: Atmos., 101, 9149–9157, https://doi.org/10.1029/96JD00334, 1996.

Guenther, A. B., Jiang, X., Heald, C. L., Sakulyanontvittaya, T., Duhl, T., Emmons, L. K., and Wang, X.: The Model of Emissions of Gases and Aerosols from Nature version 2.1 (MEGAN2.1): an extended and updated framework for modeling biogenic emissions, Geosci. Model Dev., 5, 1471–1492, https://doi.org/10.5194/gmd-5-1471-2012, 2012.

Guo, S., Wang, Y., Zhang, T., Ma, Z., Ye, C., Lin, W., Yang Zong, D. J., and Yang Zong, B. M.: Volatile organic compounds in urban Lhasa: variations, sources, and potential risks, Front. Environ. Sci., 10, https://doi.org/10.3389/fenvs.2022.941100, 2022.

Huang, B., Lei, C., Wei, C., and Zeng, G.: Chlorinated volatile organic compounds (Cl-VOCs) in environment — sources, potential human health impacts, and current remediation technologies, Environ. Int., 71, 118–138, https://doi.org/10.1016/j.envint.2014.06.013, 2014.

Liu, Y., Shao, M., Fu, L., Lu, S., Zeng, L., and Tang, D.: Source profiles of volatile organic compounds (VOCs) measured in China: Part I, Atmos. Environ., 42, 6247–6260, https://doi.org/10.1016/j.atmosenv.2008.01.070, 2008.

Liu, Y., Shao, M., Kuster, W. C., Goldan, P. D., Li, X., Lu, S., and de Gouw, J. A.: Source identification of reactive hydrocarbons and oxygenated VOCs in the summertime in Beijing, Environ. Sci. Technol., 43, 75–81, https://doi.org/10.1021/es801716n, 2009.

Mellouki, A., Wallington, T. J., and Chen, J.: Atmospheric Chemistry of Oxygenated Volatile Organic Compounds: Impacts on Air Quality and Climate, Chem. Rev., 115, 3984–4014, https://doi.org/10.1021/cr500549n, 2015.

Saeaw, N. and Thepanondh, S.: Source apportionment analysis of airborne VOCs using positive matrix factorization in industrial and urban areas in Thailand, Atmos. Pollut. Res., 6, 644–650, https://doi.org/10.5094/apr.2015.073, 2015.

Sha, Q., Zhu, M., Huang, H., Wang, Y., Huang, Z., Zhang, X., Tang, M., Lu, M., Chen, C., Shi, B., Chen, Z., Wu, L., Zhong, Z., Li, C., Xu, Y., Yu, F., Jia, G., Liao, S., Cui, X., Liu, J., and Zheng, J.: A newly integrated dataset of volatile organic compounds (VOCs) source profiles and implications for the future development of VOCs profiles in China, Sci. Total Environ., 793, 148348, https://doi.org/10.1016/j.scitotenv.2021.148348, 2021.

Sindelarova, K., Granier, C., Bouarar, I., Guenther, A., Tilmes, S., Stavrakou, T., Müller, J. F., Kuhn, U., Stefani, P., and Knorr, W.: Global data set of biogenic VOC emissions calculated by the MEGAN model over the last 30 years, Atmos. Chem. Phys., 14, 9317–9341, https://doi.org/10.5194/acp-14-9317-2014, 2014.
Stein, O. and Rudolph, J.: Modeling and interpretation of stable carbon isotope ratios of ethane in global chemical transport models, J. Geophys. Res., 112, D14308, https://doi.org/10.1029/2006jd008062, 2007.
Wang, S., Wei, W., Li, D., Li, G., and Hao, J.: Characteristics of gaseous pollutants from biofuel-stoves in rural China, Atmos. Environ., 43, 4148–4154, https://doi.org/10.1016/j.atmosenv.2009.05.040, 2009.
Yu, J., Han, Y., Chen, M., Zhang, H., Chen, Y., and Liu, J.: Characteristics and Source Apportionment of Ambient VOCs in Lhasa, Environmental Science (in Chinese), 43, 113–122, https://doi.org/10.13227 /jhjkx.202104038, 2022.
Yu, X. L., Tang, J., Zhou, L. X., Xue, H. S., and Xue, X. J.: Emission Characteristics and Sources of Non-methane Hydrocarbons at Lhasa Area, Acta Scientiae Circumstantiae (in Chinese), 21, 203–207, 2001.
Yuan, B., Shao, M., Lu, S., and Wang, B.: Source profiles of volatile organic compounds associated with solvent use in Beijing, China, Atmos. Environ., 44, 1919–1926, https://doi.org/10.1016/j.atmosenv.2010.02.014, 2010.
Zhang, Y. S., Shao, M., Lin, Y., Luan, S. J., Mao, N., Chen, W. T., and Wang, M.: Emission inventory of carbonaceous pollutants from biomass burning in the Pearl River Delta Region, China, Atmos. Environ., 76, 189–199, https://doi.org/10.1016/j.atmosenv.2012.05.055, 2013.