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Severe Aromatic Hydrocarbon Pollution in the Arctic Town of Longyearbyen (Svalbard) Caused by Snowmobile Emissions

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The aromatic hydrocarbons benzene, toluene and C_2-benzenes (ethyl benzene and *m,p,o*-xylene) (BTEX) were measured during a 2-month monitoring campaign in 2007 in the Arctic town of Longyearbyen (Spitsbergen, Svalbard). Reflecting the remoteness of the location, very low mixing ratios were observed during night and in windy conditions. In late spring (April-May), however, the high frequency of guided snowmobile tours resulted in "rush-hour" maximum values of more than 10 ppb of BTEX. These concentration levels are comparable to those in European towns and are caused predominately by the outdated 2-stroke engines, which are still used by approximately 30% of the snowmobiles in Longyearbyen. During summer, peak events were about a factor of 100 lower compared to those during the snowmobile season. Emissions in summer were mainly caused by diesel-fueled heavy duty vehicles (HDVs), permanently used for coal transport from the adjacent coal mines. The documented high BTEX mixing ratios from snowmobiles in the Arctic provide an obvious incentive to change the regulation practice to a cleaner engine technology.

Introduction

The aromatic hydrocarbons benzene, toluene, and C_2-benzenes (ethyl benzene and *m,p,o*-xylene) are important components of emissions from fossil fuel combustion (*1*). The magnitude of their emissions is mainly determined by engine technology, driving behavior, and fuel composition (*2*). Although emissions of aromatic VOCs have been reduced through the introduction of catalytic converters, they are still emitted in considerable amounts (*3*). Mixing ratios are normally in the lower ppb range in urban environments in Europe and the U.S., but can reach up to several hundred ppb in cities in Asia and South America. Ratios between different aromatic hydrocarbons in urban regions, which are mostly influenced by traffic, are normally relatively stable, with toluene having the highest mixing ratios, followed by the C_2-benzenes and benzene. In developing countries and in regions with considerable biofuel usage for heating and cooking, ratios are less stable because of the competing influence of higher relative emissions of benzene from biofuel consumption (*3, 4*). Aromatic hydrocarbons have different atmospheric lifetimes, with decreasing stability in the order of benzene > toluene > C_2-benzenes (*5*). These differing lifetimes and knowledge about the ratios of these compounds at the source have been used as so-called "photochemical clocks" to assess the history of the sampled air mass at remote locations (such as average age or abundance of radicals) (*6*–*8*).

In background environments, such as the Polar regions, long travel times and distances between the primary anthropogenic source regions and the monitoring location normally prevent the shorter lived C_2-benzenes from arriving at the site in measurable mixing ratios. On the other hand, measurable mixing ratios of the longer lived benzene and toluene have been detected in the Arctic background atmosphere (e.g., Gautrois et al. (*9*)). Here the faster reacting toluene is normally measured at lower mixing ratios than benzene, which is in contrast to urban environments.

Until now studies of emissions from snowmobiles have exclusively been made in the Yellowstone National Park (U.S). Several publications and reports document the emissions of volatile organic compounds, carbon monoxide and particulates into the otherwise pristine environment (*10*–*15*). Furthermore, tests of individual snowmobiles in the Yellowstone National Park have shown that emissions of newer 4-stroke engines were lower in comparison with older 2-stroke engines (*10, 11, 13*).

In this study we have performed continuous measurements of aromatic hydrocarbons in the Arctic town of Longyearbyen (Spitsbergen, Norway) between April and June 2007. The sampling location was next to a main road and a major snowmobile track used for guided tourist tours. Mixing ratios during the snowmobile season (April/May) were compared to those in early summer, when emissions were solely related to private car usage and exhaust from heavy duty vehicles (HDVs). Averaged monthly mixing ratios at Longyearbyen are compared with values from Zurich (Switzerland) in order to put the measurements within the susceptible arctic environment into a broader perspective.

Experimental Section

Measurement Location. Continuous measurements of BTEX were conducted during a 2-month period in late spring/early summer 2007 (15 April to 16 June) in Longyearbyen, Spitsbergen (78° 13′ N, 15° 38′ E). Longyearbyen is the major settlement on Spitsbergen (the main island of the Svalbard archipelago) with a population of around 2200 people and a capacity for overnight stays for around 1000 tourists. The main economic activities are divided between tourism, coal mining, and research infrastructures (e.g., satellite receivers, stratospheric research, environmental research institutions, and the University). During the sampling period, temperatures averaged over one month ranged from −10 °C (April/May) to −2 °C (May/June). Because of the High Arctic location of the sampling site, the sun was visible during 24 h per day (midnight sun) for the entire study period. Until mid-May the snow covered ground provided the basis for snowmobile driving. This is the most important tourist attraction during this time of the year, and a considerable number of visitors take part in one or more snowmobile excursions. In addition, snowmobiles are frequently used for extensive tours in the Arctic landscape by the residents of Longyearbyen. In 2007,

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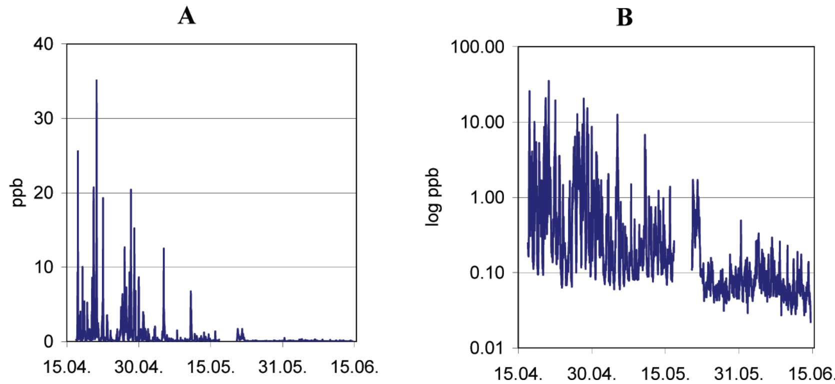

FIGURE 1. (A) Mixing ratios of the aromatic hydrocarbons (sum of benzene, toluene and C_2-benzenes) measured between mid-April and mid-June at UNIS, Longyearbyen (Spitsbergen). (B) logarithmic mixing ratios of aromatic hydrocarbons (as defined for A).

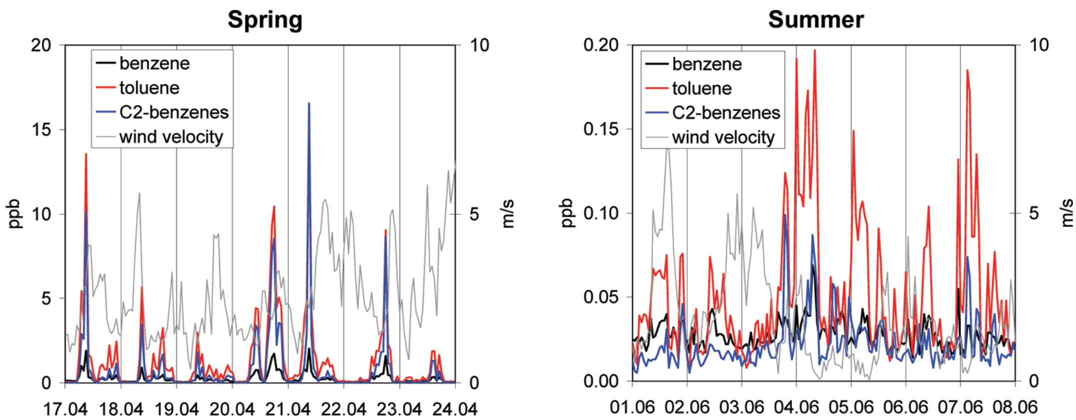

FIGURE 2. Mixing ratios of benzene, toluene and C_2-benzenes (and wind velocity) in spring (17.04.−24.04.07) and in summer (01.06.−08.06.07).

a total of 1802 snowmobiles were registered on Svalbard in the national Norwegian vehicle register.

Motivation for the Campaign. The sampling period between April and June was selected in order to cover both snowmobile activities and normal anthropogenic traffic from private cars and heavy duty vehicles. The device for continuous sampling was installed at the UNIS laboratory (the University Centre in Svalbard) located within the Research Park in Longyearbyen; 20 m from a main road and snowmobile track, where the majority of the snowmobile tour operators are located. Snowmobile "rush-hours" occurred around 9 a.m. (local time) in the morning and less distinctively in the late afternoon, when excursions were passing the sampling site.

Measurement Method. Every 15 min 200 mL of air was sampled using a 1/8" × 2 m stainless steel inlet, which was protected from icing by a plastic cup. Subsequently, samples were analyzed by gas chromatography (Syntech Spectras GC-855, Synspec, Groningen, The Netherlands) using an apolar fused-silica capillary column (BGB 2.5, 0.25 mm × 30 m; BGB, Adliswil, Switzerland) and a photoionisation detector (PID). The initial oven temperature of 50 °C was held for 3 min and was then raised to 75 °C in 3 min, where it was held constant for 5 min. Calibration was performed regularly using an NPL standard (National Physics Laboratory, Teddington, United Kingdom) in the lower ppb range. The detection limit was 0.004 ppb and precision 10% (σ) for all measured compounds. Ethyl benzene, *m*/*p*-xylene and *o*-xylene were measured individually and were lumped together as C_2-benzenes afterward. Wind and temperature measurements were obtained from the automatic meteorological station of Gruvefjellet, situated on a mountain plateau around 5 km east of Longyearbyen.

Results and Discussion

Overview. Measurements conducted between 15 April and 16 June 2007 were analyzed for the influence of snowmobile emission on the pristine local atmosphere in Spitsbergen. As an overview, Figure 1 shows the total concentration of the aromatic hydrocarbons (benzene, toluene and C_2-benzenes) at Longyearbyen. The concentration reached values of 10s of ppb in the first half of the data set, when traffic emissions were dominated by snowmobiles. A considerable decrease in the concentration could be observed after mid-May, when reduced snow coverage no longer allowed for the usage of snowmobiles. However, emissions were still present throughout the study period, originating from passenger cars and HDVs transporting coal to the Longyearbyen shipping areas from the nearby coal mine in Gruvefjellet.

Differences between Spring and Summer. In order to illustrate the difference between the two regimes (snowmobile vs HDV) in spring and summer, a representative week was chosen for both time periods (Figure 2). In spring mixing ratios of toluene and C_2-benzenes occasionally reached values above 10 ppb. Even in densely populated urban environments in central Europe these mixing ratios are rarely observed (*3*). Benzene was normally the compound with the lowest concentration, but still reached values in the ppb range. Ratios of benzene and C_2-benzenes relative to toluene were 0.14 (r^2 = 0.969) and 0.82 (r^2 = 0.933), respectively. Mixing ratios were lowest during nights and during high wind speed conditions. In summer, peak mixing ratios were roughly 2 orders of magnitude lower and more evenly spread over the course of the day. As in spring, wind speed had an influence on the magnitude of the peak values.

Analysis of Daily Cycles. For a more in depth discussion daily cycles between mid-April to mid-May (i.e., when

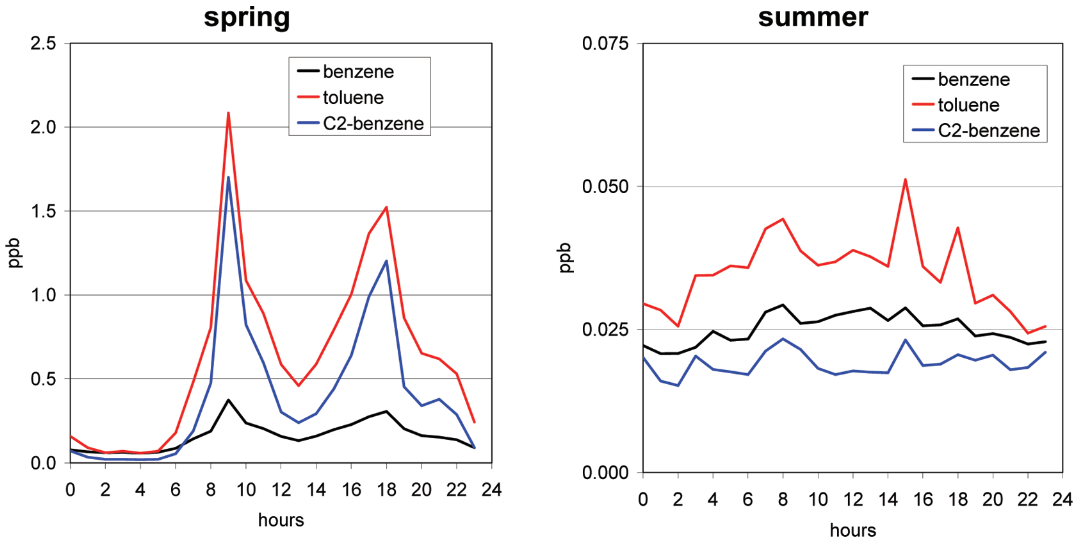

FIGURE 3. Daily cycles of benzene, toluene and C_2-benzenes in spring (mid-April to mid-May) and summer (mid-May to mid-June) at Longyearbyen (Spitsbergen).

snowmobiles were used) and mid-May to mid-June (when only gasoline and diesel-fueled vehicles were used) are shown in Figure 3. In spring, two peak values were observed over the course of the day. The relatively sharp morning peak represented the simultaneous start of the snowmobile excursions at around 9 a.m. (local time). In the afternoon, the peak values were spread over a broader period of time (and are therefore less pronounced), as the return of the different snowmobile excursions depended on the traveled distance. During peak events, absolute mixing ratios of aromatic hydrocarbons were approximately factors of 6, 30, and 50 times higher than during the night for benzene, toluene, and C_2-benzenes, respectively. Thereby, the night values approximately represented the background conditions in the winter high-latitude Northern hemisphere, with the most reactive group of substances (i.e., C_2-benzenes) showing the lowest concentration. However, the finding that toluene had on average roughly the same concentration as the less reactive benzene could indicate that local emissions of diesel-fueled HDVs (running for 24 h a day) could also have had an effect.

Fuel Consumption of Snowmobiles in Spitsbergen. In order to assess the emissions of snowmobiles in Longyearbyen, the ratios of specific hydrocarbons during spring were combined with fuel consumption and published emission figures from snowmobiles in the U.S. (*10, 11*). In 2007, 1802 snowmobiles were registered in Spitsbergen, of which 30% were 2-stroke engines and 70% were 4-stroke engines. None of the snowmobiles were equipped with catalytic converters. Kallenborn et al. (*16*) estimated the average mileage driven by snowmobiles in Spitsbergen to be about 2000 km/year. Using consumption numbers from Bishop et al. (*10*) of 136 g/km for 2-stroke engines and 99 g/km for 4-stroke engines (Table 1), this accounts to a fuel consumption of 196 000 Liters (147 tons) for the 540 2-stroke snowmobiles and 332 000 Liters (250 tons) for the 1260 4-stroke snowmobiles.

Total Hydrocarbon Emissions from Snowmobiles. Emissions of the total amount of hydrocarbons (losses of unburnt fuel) from 2-stroke and 4-stroke snowmobiles were assessed in Yellowstone National Park by using remote sensing (*10–12*). For calculating the fuel losses in Longyearbyen the respective figures of 92 g/mile/passenger for 2-stroke and 3.4 g/mile/passenger for 4-stroke snowmobiles in Yellowstone National Park (*10*) were converted to 69 g/km (for 2-stroke), and 2.5 g/km (for 4-stroke snowmobiles) (Table 1). Thereby, the average number of 1.6 passengers/snowmobile was used as indicated in (*10*). By comparing these losses with total fuel usage, it can be calculated that 51% of the fuel leaves the 2-stroke snowmobiles exhaust pipe unchanged, whereas only 2.5% of the fuel is lost from the 4-stroke snowmobiles. By relating the losses to the consumption and travel distances of snowmobiles in Spitsbergen, yearly emissions of 80.8 t of hydrocarbons could be calculated for 2007 (Table 2). Interestingly, the 30% of 2-stroke engines contributed more than 90% of the total emissions (74.5 t/year), which makes their reduction in the fleet a highly priority for emission reductions.

TABLE 1. Fuel Consumption and Emissions of Hydrocarbons from 2-Stroke and 4-Stroke Snowmobiles (*10*)[a]

	2-stroke	4-stroke
consumption [miles/gallon]	13 miles/gallon	18 miles/gallon
consumption [L/100 km]	18.1 L/100 km	13.1 L/100 km
consumption [g/km]	136 g/km	99 g/km
total hydrocarbon emission	69 g/km	2.5 g/km

[a] One mile/gallon × 235.21 = L/100 km, gasoline density = 0.75 kg/L.

Aromatic Hydrocarbon Emissions from Snowmobiles. For the calculation of aromatic hydrocarbon emissions in Spitsbergen, the ratio of toluene/total hydrocarbons of 8%, which was found in snowmobile emissions by Bishop et al. (*11*), has been used as a starting point. This ratio has been derived by a small number of 2-stroke engines in the late 1990s in Yellowstone National Park. Therefore, it has to be taken as a best estimate, although emissions in Spitsbergen are also dominated by older 2-stroke engines. Connecting this ratio with the total emissions of 80.8 t/year, toluene emission from snowmobile driving in Spitsbergen was calculated to be around 6.5 t/year. Emissions of benzene and C_2-benzenes have been calculated using their relative ratios to toluene of 0.14 and 0.82, respectively, which were determined during the spring period in Longyearbyen. Resulting emissions from snowmobiles in Spitsbergen were ~0.9 t/year for benzene and ~5.3 t/year for C_2-benzenes (Table 2).

Summer Conditions without Snowmobiles. After mid-May, emissions from snowmobiles were no longer present as the snowmelt no longer allowed their operation in Longyearbyen. Therefore, emissions of aromatic hydrocarbons in June were most likely caused by diesel and gasoline cars as well as diesel HDVs. In Spitsbergen around 650 cars are registered, of which 60% are diesel and 40% are gasoline-

TABLE 2. Emissions of Aromatic Hydrocarbons from Snowmobiles and Cars/HDVs in Spitsbergen[a]

Emissions in Longyearbyen from Snowmobiles

	emissions (g/km)		total emissions Spitsbergen (t/year)		
	2-stroke (no. 540)	4-stroke (no. 1260)	2-stroke	4-stroke	total
total HC	69	2.5	74.5	6.3	80.8
benzene	0.76	0.03	0.82	0.07	0.89
toluene	5.52	0.20	5.96	0.50	6.46
C_2-benzenes	4.56	0.17	4.91	0.42	5.33

Emissions in Longyearbyen from Cars and HDVs

	emissions (g/km)			total emissions Spitsbergen (t/year)			
	cars gasoline (no. 260)	cars diesel (no. 390)	HDVs diesel (no. 88)	cars gasoline	cars diesel	HDVs diesel	total
total HC	2.347	0.414	1.038	1.526	0.404	9.134	11.1
benzene	0.101	0.008	0.014	0.065	0.008	0.121	0.20
toluene	0.222	0.018	0.031	0.144	0.018	0.273	0.44
C_2-benzenes	0.091	0.007	0.013	0.059	0.007	0.114	0.18

[a] Left-hand panel: emissions Per Distance [g/km]. Right-hand panel: integrated emissions for Spitsbergen [t/year]. Average driving distance as assumed by Kallenborn et al. (*16*): snowmobiles: 2′000 km/year; diesel and gasoline cars: 2500 km/year; diesel HDVs: 100 000 km/year.

fueled. Furthermore, diesel-fueled HDVs are used for the transport of coal from the nearby mine to the harbor. Peak events were about a factor of 100 times lower than in spring, although still visible (Figures 1 and 2). Ratios between specific aromatic hydrocarbons were still not representative for Arctic background conditions, where the more stable benzene should be dominant and the most reactive C_2-benzenes should be less prevalent (*9*). During pollution events, toluene was the dominant compound and C_2-benzenes and benzene were roughly a factor of 2 smaller (Figures 2 and 3). This is indicative of fresh emissions from gasoline and diesel-fueled cars (*2, 17*).

Total Hydrocarbon Emissions from Road Traffic. Total hydrocarbon emissions of cars and HDVs were estimated using measurements of both engine types in a dynamometer test stand at a temperature of −7 °C (*2, 18*). For gasoline-fueled and diesel-fueled passenger cars cold-start emissions were used, as in Spitsbergen most of the vehicle operation is performed within a few minutes after engine start because of the very small road system. For HDVs emissions were also taken at −7 °C but from the warm phase of the driving cycle. HDVs in Longyearbyen are driven mostly throughout the day to transport coal from the mine to the harbor. The different driving habits of cars and HDVs are also expressed in the average annual driving distance of 2500 km/year for passenger cars and 100 000 km/year for HDVs (*16*). Furthermore, to account for the approximately 6 times higher fuel consumption of diesel HDVs relative to diesel cars, warm-phase emissions from diesel cars were multiplied by a factor of 6.

Aromatic Hydrocarbon Emissions from Road Traffic. Emissions of aromatic hydrocarbon species were estimated using emission factors from Weilenmann et al. (*2*) and Stettler et al. (*18*) for benzene. Emissions for toluene and C_2-benzenes were calculated relatively to their ratios to benzene in June (extracted from the mixing ratios above the background of the daily cycles (Figure 3)). Because this approach depends on the accurate subtraction of baseline concentrations, the resulting emissions for specific aromatic hydrocarbons shown in Table 2 should be regarded as indicative. Although emissions per km are higher for the gasoline-fueled cars, total emissions are dominated by the diesel-fueled HDVs. This dominating effect of diesel HDVs, which transport coal 24 h per day, results in a rather homogeneous distribution of the average daily cycle (Figure 3), although peak events occasionally occur at night (Figure 2). In total, cars emit ~2 t of hydrocarbons and HDVs ~9 t of hydrocarbons. The total of 11 t of hydrocarbons emitted by road traffic in Spitsbergen represents 12% of the total hydrocarbon emissions, with snowmobiles being responsible for the predominant fraction of hydrocarbon emissions (88%). The even higher proportion of measured mixing ratios in spring (caused by snowmobiles) versus those in summer (caused by road traffic) in Longyearbyen is based on the fact that snowmobile emissions were dominated by morning and afternoon rush-hours. In summer emissions are more evenly distributed because the 24 h day light favoring round the clock activities and coal transport by HDVs.

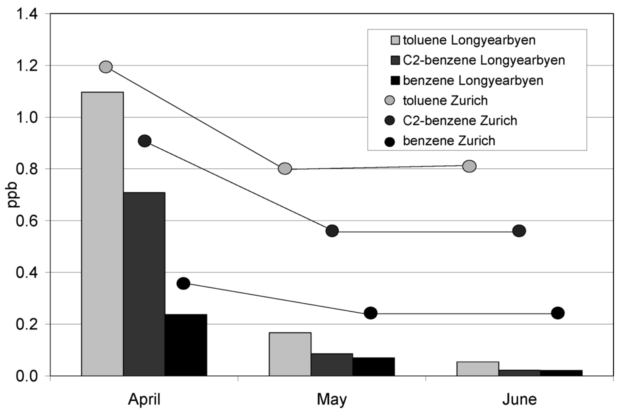

FIGURE 4. Monthly average mixing ratios of benzene, toluene and C_2-benzenes at Longyearbyen (Spitsbergen) and Zurich (Switzerland) in April−June 2007.

Comparison with Urban European Conditions. As an attempt to put the mixing ratios of the aromatic hydrocarbons in the Arctic settlement of Longyearbyen into context with normal European conditions, the BTEX mixing ratios in 2007 were compared with those from the same period in Zurich (Switzerland). In Zurich peak events are mostly caused by emissions from traffic, and to a minor degree from industry (*19*) (Figure 4). Amazingly, average mixing ratios in the spring months in Longyearbyen were nearly as high as in Zurich, although the number of inhabitants is more than a factor of 100 higher in Zurich (Zurich: 370 000, Longyearbyen (including tourists): ~3000). In summer, mixing ratios in Zurich decrease slightly as the influence of cold starts gets lower and the warmer temperatures favor the exchange with the surrounding area. In Longyearbyen mixing ratios in summer decline dramatically as snowmobile driving is not possible at this time of the year.

Suggestions for Emission Reductions. The relatively high concentrations of BTEX identify a need for action regarding the emissions from snowmobiles into the otherwise nearly pristine Arctic environment. In order to decrease emissions to an acceptable level the replacement of the older 2-stroke engines with 4-stroke engines is of paramount priority. If exclusively 4-stroke snowmobiles were used, their total emissions would be comparable to those from road traffic. Furthermore, snowmobiles could be fitted with catalytic converters. Installation of catalytic converters, which is compulsory in Europe for motorcycles, seems like a straightforward idea. However, Saxer et al. (*20*) found that catalytic converters fitted to motorcycles (which in terms of engine technology are comparable to snowmobiles) reduced emissions of aromatic hydrocarbons only during warm engine conditions, whereas during the cold start emissions could be more than a factor of 3 higher. This implies that catalytic converters for snowmobiles will be positive for the Arctic environment as a whole, but will have an adverse effect for the mixing ratios in the settlement of Longyearbyen, unless they are preheated. In order to even further decrease hydrocarbon emissions in Spitsbergen, the replacement of the heavy polluting diesel-fueled HDVs, which also emit considerable amounts of particles, should be targeted. This could be done by installation of a transport cable car between the mines and the harbor. Such a system was already in operation in Longyearbyen in former times, but was abandoned decades ago. With all these measures, emissions of hydrocarbons in Spitsbergen could be reduced by an order of magnitude to less than 10 t/year.

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Literature Cited

(1) Heeb, N. V.; Forss, A. M.; Bach, C.; Reimann, S.; Herzog, A.; Jackle, H. W. A comparison of benzene, toluene and C-2-benzenes mixing ratios in automotive exhaust and in the suburban atmosphere during the introduction of catalytic converter technology to the Swiss car fleet. *Atmos. Environ.* **2000**, *34* (19), 3103–3116.

(2) Weilenmann, M.; Soltic, P.; Saxer, C.; Forss, A. M.; Heeb, N. Regulated and nonregulated diesel and gasoline cold start emissions at different temperatures. *Atmos. Environ.* **2005**, *39*, 2433–2441.

(3) Reimann, S. and Lewis, A. C. *Anthropogenic VOCs, in: Volatile Organic Compounds in the Atmosphere*; Koppmann, R., Ed.; Blackwell Publishing: Cambridge, MA, 2007.

(4) Gaeggeler, K.; Prevot, A. S. H.; Dommen, J.; Legreid, G.; Reimann, S.; Baltensperger, U. Residential wood burning in an Alpine valley as a source for oxygenated volatile organic compounds, hydrocarbons and organic acids. *Atmos. Environ.* **2008**, *42* (35), 8278–8287.

(5) Atkinson, R.; Baulch, D. L.; Cox, R. A.; Crowley, J. N.; Hampson, R. F.; Hynes, R. G.; Jenkin, M. E.; Rossi, M. J.; Troe, J. Evaluated kinetic and photochemical data for atmospheric chemistry. Vol. II—gas phase reactions of organic species. *Atmos. Chem. Phys.* **2006**, *6*, 3625–4055.

(6) Arnold, S. R. Methven, J. Evans, M. J. Chipperfield, M. P. Lewis, A. C. Hopkins, J. R. McQuaid, J. B. Watson, N. Purvis, R. M. Lee, J. D. Atlas, E. L. Blake, D. R. and Rappengluck, B. Statistical inference of OH concentrations and air mass dilution rates from successive observations of nonmethane hydrocarbons in single air masses. *J. Geophys. Res., [Atmos.]*, **2007**. *112* (D10).

(7) Ehhalt, D. H.; Rohrer, F.; Wahner, A.; Prather, M. J.; Blake, D. R. On the use of hydrocarbons for the determination of tropospheric OH concentrations. *J. Geophys. Res., [Atmos.]* **1998**, *103* (D15), 18981–18997.

(8) Blake, N. J.; Penkett, S. A.; Clemitshaw, K. C.; Anwyl, P.; Lightman, P.; Marsh, A. R. W.; Butcher, G. Estimates of atmospheric hydroxyl radical concentrations from the observed decay of many reactive hydrocarbons in well-defined urban plume. *J. Geophys. Res., [Atmos.]* **1993**, *98* (D2), 2851–2864.

(9) Gautrois, M.; Brauers, T.; Koppmann, R.; Rohrer, F.; Stein, O.; Rudolph, J. Seasonal variability and trends of volatile organic compounds in the lower polar troposphere. *J. Geophys. Res., [Atmos.]* **2003**, *108*, D13.

(10) Bishop, G. A.; Burgard, D. A.; Dalton, T. R.; Stedman, D. H.; Ray, J. D. Winter motor-vehicle emissions in Yellowstone National Park. *Environ. Sci. Technol.* **2006**, *40* (8), 2505–2510.

(11) Bishop, G. A.; Morris, J. A.; Stedman, D. H. Snowmobile contributions to mobile source emissions in Yellowstone National Park. *Environ. Sci. Technol.* **2001**, *35* (14), 2874–2881.

(12) Bishop, G. A.; Stedman, D. H.; Hektner, M.; Ray, J. D. An in-use snowmobile emission survey in Yellowstone National Park. *Environ. Sci. Technol.* **1999**, *33* (21), 3924–3926.

(13) Shively, D. D.; Pape, B. M. C.; Mower, R. N.; Zhou, Y.; Russo, R.; Sive, B. C. Blowing smoke in Yellowstone: Air quality impacts of oversnow motorized recreation in the park. *Environ. Manage.* **2008**, *41* (2), 183–199.

(14) Sive, B. Shively, D. and Pape, B. Spatial Variation of Volatile Organic Compounds Associated with Snowmobile Emissions in Yellowstone National Park, 2003 (report)http://www.nps.gov/yell/parkmgmt/upload/sive_report.pdf.

(15) Ray, J. D. Winter Air Quality in Yellowstone National Park: 2007−2008, Natural ResourceTechnical Report NPS/NRPC/ARD/NRTR-2008/139; National Park Service: Fort Collins, CO, 2008; http://www.nps.gov/yell/parkmgmt/upload/aq70-08__final.pdf.

(16) Kallenborn, R.; Oekstad, E.; Vestreng, V. Emission inventory of certain greenhouse gases in Svalbard *Nat. Norw. Rep.* **2009.**

(17) Caplain, I. Cazier, F. Nouali, H. Mercier, A. Dechaux, J. C. Nollet, V. Journard, R. Andre, J. M. and Vidon, R. Emissions of Unregulated Pollutants from European Gasoline and Diesel Passenger Cars. *13th International Symposium on Transport and Air Pollution*, Boulder, CO 2004.

(18) Stettler, P.; Weilenmann, M.; Forss, A.-M.; Mohr, M. *Nachführung der Emissionsgrundlagen Strassenverkehr Messungen 01−02 Benzinpersonenwagen Euro-0 und Euro-3 sowie Dieselpersonenwagen Euro-2*, Empa report 202114; Empa: Dübendorf, Switzerland, 2004.

(19) Lanz, V.; Hueglin, C.; Buchmann, B.; Hill, M.; Locher, R.; Staehelin, J.; Reimann, S. Receptor modeling of C2-C7 hydrocarbon sources at an urban background site in Zurich, Switzerland: Changes between 1993−1994 and 2005−2006. *Atmos. Chem. Phys.* **2008**, *8*, 2313–2332.

(20) Saxer, C. J.; Forss, A. M.; Rudy, C.; Heeb, N. V. Benzene, toluene and C-2-benzene emissions of 4-stroke motorbikes: Benefits and risks of the current TWC technology. *Atmos. Environ.* **2006**, *40*, 6053–6065.

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