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Abstract

In August 2010, simultaneous enhancements of aerosol optical depth and total columns of carbon monoxide (CO), hydrogen cyanide (HCN), and ethane (C₂H₆) were observed at the Polar Environment Atmospheric Research Laboratory (PEARL, 80.05°N, -86.42°W, 0.61 km above sea level, Eureka, Nunavut, Canada). Moderate Resolution Imaging Spectroradiometer (MODIS) hot spots, Ozone Monitoring Instrument (OMI) aerosol index maps, and Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) back-trajectories were used to attribute these enhancements to an intense boreal fire event occurring in Russia. A ground-based Fourier Transform InfraRed (FTIR) spectrometer at PEARL provided vertically integrated measurements of trace gases transported in smoke plumes. We derived HCN and C₂H₆ equivalent emission ratios with respect to CO of 0.0054 ± 0.0022 and 0.0108 ± 0.0036 , respectively, and converted them into equivalent emission factors of 0.66 ± 0.27 g kg⁻¹ and 1.47 ± 0.50 g kg⁻¹ (in grams of gas per kilogram of dry biomass burnt, with one-sigma uncertainties). These emission factors add new observations to the relatively sparse datasets available and can be used to improve the simulation of biomass burning fire emissions in chemical transport models. These emission factors for the boreal forest are in agreement with the mean values recently reported in a compilation study.

Keywords

russian, boreal, forest, hcn, fires, canadian, columns, total, high, arctic, co, c₂h₆, smoke, plumes, transported, 2010, measurements

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Measurements of CO, HCN and C₂H₆ total columns in smoke plumes transported from the 2010 Russian boreal forest fires to the Canadian high Arctic

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Abstract

In August 2010, simultaneous enhancements of aerosol optical depth and total columns of carbon monoxide (CO), hydrogen cyanide (HCN), and ethane (C₂H₆) were observed at the Polar Environment Atmospheric Research Laboratory (PEARL, 80.05°N, -86.42°W, 0.61 km above sea level, Eureka, Nunavut, Canada). Moderate Resolution Imaging Spectroradiometer (MODIS) hot spots, Ozone Monitoring Instrument (OMI) aerosol index maps and HYSPLIT back-trajectories were used to attribute these enhancements to an intense boreal fire event occurring in Russia. A ground-based Fourier Transform InfraRed (FTIR) spectrometer at PEARL provides vertically integrated measurements of trace gases transported in smoke plumes. We derived HCN and C₂H₆ equivalent emission ratios with respect to CO of 0.0054 ± 0.0022 and 0.0108 ± 0.0036 , respectively, and converted them into equivalent emission factors of 0.66 ± 0.27 g kg⁻¹ and 1.47 ± 0.50 g kg⁻¹ (in grams of gas per kg of dry biomass burnt, with one-sigma uncertainties). These emission factors add new observations to the relatively sparse datasets available, and can be used to improve the simulation of biomass burning fire emissions

in chemical transport models. These emission factors for the boreal forest are in agreement with the mean values recently reported in a compilation study.

keywords : atmosphere, FTIR measurements, Arctic, biomass burning, boreal fire, emission factors.

I) Introduction

Fires release considerable amounts of radiatively and photochemically active trace gases, such as carbon monoxide (CO), hydrogen cyanide (HCN), and ethane (C₂H₆), as well as aerosols (IPCC, 2007; Zhao et al., 2002). Biomass burning has been suggested as an important source of Arctic pollution: boreal fires in Siberia, Canada, and Alaska represent a major perturbation to the Arctic atmosphere in summer, affecting the carbon cycle (Preston and Schmidt, 2006), climate (Amiro et al., 2001), air quality (Colarco et al., 2004), and land ecology (Soja et al., 2007). Several studies have identified biomass burning pollution transport to the Arctic on the basis of model simulations (e.g., Shindell et al., 2008) and aerosol observations (e.g., Saha et al., 2010), but our ability to observe fire plumes in term of vertically integrated chemical composition has been limited. The Polar Environment Atmospheric Research Laboratory (PEARL) located at Eureka, Nunavut, Canada is appropriately situated for sampling the outflow of boreal biomass burning pollution over the Arctic region and is equipped with a Fourier Transform InfraRed (FTIR) spectrometer and a sunphotometer to measure trace gases and aerosols, respectively. To quantify the atmospheric impact of biomass burning in chemical transport models, emission factors of trace gases must be implemented accurately, but those factors are highly variable because they depend on the types of vegetation burned, the combustion phase (smoldering and flaming), and on atmospheric conditions at the time of the fire events (Paton-Walsh et al., 2004, 2005, 2010;

Vigouroux et al., 2012). Considering their long lifetimes, HCN and C₂H₆ are considered to be tracers of pollution transport such as that found in biomass burning plumes. Within the past decade, measurements of emission factors of HCN and C₂H₆ have led to a wide range of values, which may be due to the natural variability of the emissions and/or the discrepancies between sampling methods (laboratory, airborne, satellite, and ground-based measurements) that overestimates or underestimates the combustion phases (smoldering and flaming). Andreae and Merlet (2001) stressed the need for more measurements of HCN emission factors given its value as biomass burning tracer (Li et al., 2000). Concerning C₂H₆, recent work shows that biomass fires emit more Non Methane Hydrocarbons (including ethane) than previously thought and that may improve the chemical model performance (Akagi et al., 2011).

That is why, in this study, precise FTIR measurements of trace gas columns inside smoke plumes are used to assess emission factors in order to add new observations to the sparse datasets that have been reported and compiled in the literature (Andreae and Merlet, 2001; Akagi et al., 2011).

2) Measurements and analysis

a) FTIR measurements

The FTIR spectrometer (a Bruker IFS 125HR) located at PEARL and operational since August 2006, is part of the Network for the Detection of Atmospheric Composition Change (NDACC, <http://www.ndsc.ncep.noaa.gov/>) and the Total Carbon Column Observing Network (TCCON, <http://www.tccon.caltech.edu/>). Trace gas columns such as biomass burning products CO, HCN, and C₂H₆ are derived from individual solar absorption spectra in the middle infrared region for NDACC (2057.7-2159.3 cm⁻¹ for CO, 3268.0-3287.5 cm⁻¹ for HCN, and 2976.6-2987.0 cm⁻¹ for C₂H₆) and in the near infrared region for TCCON (4233-4290 cm⁻¹ for CO) (Bachelor et al.,

2009; Lindenmaier, 2012). NDACC and TCCON measurements are made successively because beamsplitters have to be changed for acquisition. The HITRAN 2008 line parameters (Rothman et al., 2009) were used in both the NDACC and TCCON analysis and all the interfering species inside these micro-windows were scaled from a priori profiles.

For the NDACC measurements, total columns of all three molecules are retrieved using the iterative fitting algorithm SFIT2 (Rinsland et al., 1998) based on the Optimal Estimation Method (OEM) of Rodgers (2000), with a priori Volume Mixing Ratio (VMR) profiles for every gas based on the mean of a 40-year run (1980-2020) from the Whole Atmosphere Chemistry Climate Model (WACCM, v5, Eyring et al. (2007)) for Eureka (J. Hannigan, NCAR, personal communication). The retrieved vertical profiles are obtained on a 48-level altitude grid (from 0.61 to 120 km). Total columns are then derived by vertically integrating retrieved profiles. Total columns are then derived by vertically integrating retrieved profiles. The diagonal elements of the a priori covariance matrix are used as a tuning parameter, i.e. they are optimized empirically to stabilize the retrievals and maximize the spectral information. We used 50%, 20% and 30% as the one sigma variability to generate the diagonal elements of the covariance matrix for HCN, CO and C₂H₆ respectively. These values are consistent with the natural tropospheric variabilities derived from the WACCM model. Full error analysis is performed following the formalism of Rodgers (2000), and can be divided into three different error sources: the smoothing error expressing the uncertainty due to the limited vertical resolution of the retrieval, the forward model parameter error, and the measurement noise error. Typical total uncertainties on total columns (including smoothing, temperature, and measurement errors, spectroscopic line width and line intensity uncertainties, and solar zenith angle error, added in quadrature) are 2.5%, 9.0%, and 3.5% for CO, HCN, and C₂H₆, respectively. Average degrees of freedom for signal,

over the 2007 to 2011 period, are 2.8, 1.6, and 1.9 for CO, HCN, and C₂H₆ total columns, respectively. For the TCCON retrievals of CO, the GFIT non-linear least-square fitting algorithm is used to scale a priori VMR profiles, which are derived from ACE-FTS climatology, in order to generate the best spectral fit, with a total column error of 2% (Wunch et al., 2011). During the fire event of August 2010, 61 individual middle infrared spectra were recorded through the smoke plume from August 9th to 30th, 2010 and 41 near infrared spectra recorded on August 23rd confirmed the rapid enhancement of CO columns on that day. Smoke aerosol is not explicitly included in the spectral fits given that any spectral signatures will be broad compare to the narrow fitting micro-windows. Both NDACC and TCCON spectra and fits have to satisfy quality filters based on signal-to-noise ratios, baseline distortions, fitting residuals. This ensures to optimize the quality of all measurements and retrievals.

b) Aerosol measurements

Spectral solar irradiance and almucantar radiance is measured by a Cimel sunphotometer/sky radiometer belonging to the AEROCAN/AERONET networks (AEROCAN is a federated Canadian subnetwork of the worldwide, NASA-led AERONET network, <http://aeronet.gsfc.nasa.gov/cgi-bin/>). It is located at PEARL and has been operational since March 2007. The Cimel instrument, as well as AERONET measurement protocols, are described by Holben et al. (1998). The PEARL Aerosol Optical Depths (AODs) are acquired in a high-frequency (3-minute) temporal mode. Total, fine, and coarse mode AODs at 500 nm are retrieved using the Spectral Deconvolution Algorithm (SDA, AERONET Version 2.0) of O'Neill et al. (2003). We used level 2.0 AERONET to ensure data quality control.

c) IASI satellite measurements

Global CO concentrations are retrieved daily from space-borne Infrared Atmospheric Sounding Interferometer (IASI) radiance spectra using the Fast Optimal Retrievals on Layers for IASI (FORLI) software (Clerbaux et al., 2009; Hurtmans et al., 2012). The quality of IASI FORLI-CO retrievals has been evaluated for highly polluted conditions due to wildfires (Turquety et al., 2009) and recently by comparing with NDACC FTIR measurements (Kerzenmacher et al., 2012). Data are available at ether.ipsl.jussieu.fr/php/test2.php.

d) Calculation of emission factors

Trace gas concentrations within smoke plumes vary rapidly with time, so a common way of deriving an emission factor is to measure the emission ratio of the target chemical species relative to a reference species, which is often CO₂ or CO (Hurst et al., 1994). Here we use CO as the reference since variations of CO₂ concentration are difficult to measure with sufficient accuracy. Because the emission ratio is not measured here at the source of the fire, it is more accurately called an “enhancement ratio”. These ratios are derived from the regression slope of a given trace gas total column versus that of CO.

For comparison with previous studies, our enhancement ratios (i.e, equivalent emission ratios) have been converted into equivalent emission factors using (Andreae and Merlet, 2001):

$$EF_x = ER_{(x/CO)} \times (MW_x/MW_{CO}) \times EF_{CO} \quad (1)$$

where EF_x is the emission factor for trace gas X in grams of gas per kg of dry biomass burnt; $ER_{(x/CO)}$ is the molar emission ratio of trace gas X with respect to CO; MW_x is the molecular weight of trace gas X; MW_{CO} is the molecular weight of CO, and EF_{CO} is the emission factor of CO.

In this study, values of EF_{CO} of $127 \pm 45 \text{ g kg}^{-1}$ and $107 \pm 37 \text{ g kg}^{-1}$ for dry matter based on Akagi et al. (2011) and Andreae and Merlet (2001) are taken as the mean emission factor for CO for boreal and extratropical forests, since it is the fuel type of the source fires which were burning. Uncertainties on the measured EF_{CO} are calculated by taking into account the large uncertainty in the CO emission factor (more than 35%) and the uncertainty in the calculated regression slope (7.9% and 5.0% for HCN and C_2H_6 , respectively), as well as the total uncertainties of the retrievals, all combined in quadrature (Paton-Walsh et al., 2005).

3) Measurement of biomass burning products

a) Trace gas total columns and AODs at Eureka in August 2010

Figure 1a presents the time series of the FTIR CO (both TCCON and NDACC), HCN and C_2H_6 total columns, from the 9th to the 30th of August 2010, where simultaneous enhancement of the three biomass burning species, with a sharp increase on August 23rd (yellow box) and persistent elevated concentrations from that day to the 29th, can be seen. Focusing on August 23rd, Figure 1b shows that the CO total columns measured by the FTIR increase from 1.8×10^{18} molecules cm^{-2} at 15:00 UT to 2.1×10^{18} molecules cm^{-2} at 22:00 UT on that day. Furthermore, Figure 1c shows the IASI CO total column distribution over the Eureka area on August 23rd, where a local enhancement of CO is clearly observed. The IASI higher CO total columns may be due to the potential bias of the thermal emission instrument sensitivity, which is higher in summer. In addition, Figure 1b shows that fine-mode AODs increase throughout that day whereas coarse-mode AODs remain constant. This suggests the presence of a smoke plume inasmuch as fine-mode AODs can be traced to fire events, whereas coarse-mode AODs are characteristic of thin homogeneous clouds, marine aerosols, ash and/or dust in the atmosphere.

This event is significant but rather weak in terms of smoke-induced, fine-mode AOD variation at Eureka; the variation, < 0.04 , is comparable to late-spring / summertime observations made by O'Neill et al. (2008) but significantly less than the strong springtime smoke events observed by Saha et al. (2010) during the ARCTAS campaign of 2008.

b) Origin and path of the plume

During summer 2010, intense drought and high temperatures, led to several hundred wildfires over Russia. Indeed, July 2010 was considered the warmest month in Moscow since the beginning of modern meteorological recording 130 years ago. The total vegetated area (forest, vegetation and peat land) affected by wildfires on Russian territory reached around five million hectares by early August 2010, leading to a total CO emission between 34 and 40 Tg CO during July and August 2010 [Yurganov et al., 2011]. MODIS and Multi-angle Imaging Spectroradiometer (MISR) images indicate that smoke extended over about 3,000 km (from east to west) in early August and sometimes reached altitudes of 12 km, an altitude at which the plume may travel long distances to affect air quality far away.

Figure 2 is a graphical ensemble of evidence illustrating the origin and path of the plume that reached PEARL during August 2010. According to HYSPLIT back-trajectories (Figure 2a), air masses that arrived on August 24th at PEARL (at 5, 7 and 9 km altitude, <http://ready.arl.noaa.gov/hysplit-bin/>) originated in Russia nine days earlier, where red dots (Figure 2b) represent the 10-day (August 9th-18th) average of fire hot spots identified by the MODIS instrument (<http://lance-modis.eosdis.nasa.gov/cgi-bin/imagery/firemaps.cgi>). To support this idea, a MODIS image (Figure 2c) taken on August 15th at 9:00 UT has been superimposed on the trajectory plot (yellow box). One can see that all three dots (red, blue and

green, Figure 2c), representing the air mass locations at the same time as the MODIS image, are inside a fire area (red dot) or close to the smoke plume. Additional evidence of intense fire events in the Moscow area is illustrated in Figures 2d, which presents high values of UV aerosol index derived from OMI measurements (<http://gdata1.sci.gsfc.nasa.gov/daac-bin/>) in the same fire region (yellow box) and for the same day. Back-trajectories for the beginning of August 2010 confirm that Russian fire affected atmospheric composition at Eureka but are not shown here since their patterns are less clear than the ones for August 24th.

4) Results

a) Trace gas correlations

The HCN total columns from the 9th to the 30th August 2010 are enhanced by more than 50% compared to the four-year (2008-2011) monthly mean of 5.24×10^{15} molecules.cm⁻² for August measurements at PEARL. Also, all August 2010 measurements (red dots, Figures 3a and 3c) give a similar slope in the correlation plots, therefore all these data (from the 9th to the 30th of August) are considered to be fire-affected.

The C₂H₆ total columns have been plotted against CO (NDACC-only) for all (1447) spectra recorded in 2010 (Figure 3a, black) and those for the fire period of August 2010 (Figure 3a, red). Columns of C₂H₆ and CO are correlated over the year due to their common sink via reaction with OH (Rinsland et al., 1998, 1999, 2000), therefore the seasonal variability of these molecules is identical throughout the year, with maxima in winter-spring (February-March) and minima in summer-fall (August-September) (Zhao et al., 2002). However, the correlation slope for the August columns differs from the annual one. The high correlation ($R = 0.94$) between C₂H₆ and CO total columns is consistent for all 58 spectra recorded during the fire period (Figure 3b).

Figure 3c shows the HCN total columns measured during all of 2010 (1578 spectra), plotted against the co-located (NDACC-only) measurements of CO. No correlation is seen between HCN and CO total columns throughout the year, due to different atmospheric chemistry processes controlling the abundance of these two molecules, but a correlation is present in the August data (red dots, Figure 3c). Figure 3d confirms this correlation since the coefficient of correlation between the 61 HCN and CO total columns measured in August when the smoke plume from Russia was transported over PEARL is 0.85.

b) Emission factors for biomass burning species

The HCN and C₂H₆ emission factors have been derived by using Equation 1, and taking the values of the regression slopes as emission ratios. Because CO, HCN and C₂H₆ lifetimes are relatively long in the atmosphere (around 2, 5 and 1.5 months respectively, Müller and Brasseur, 1995; Li et al., 2003; Xiao et al., 2008), decay rates of each chemical species have been calculated by considering the exponential decrease after nine days, given their relative lifetimes (i.e., for CO, the decay rate is $\exp(-9/61)$). Typical lifetimes were used based on literature values that assumed climatological OH fields. Therefore, CO, HCN, and C₂H₆ abundances in the nine-day-old aged smoke plume should be 86.3%, 94.2% and 81.9% of their initial values, respectively, assuming there are no local sources along the trajectories from Russia. Therefore, the measured HCN and C₂H₆ enhancement ratios will differ by a factor of 1.091 (=94.2/86.3) and 0.9488 (=81.9/86.3) relative to the original emission ratios, meaning that those measured ratios are 9.1% higher and 5.1% lower than the emission ratios, respectively. Thus, we have corrected the measured enhancement ratios by taking into account the effect of the aging of the smoke plume in order to derive equivalent emission ratios. Since the uncertainty in the correction is

small compared to other uncertainties, our equivalent emission ratios can be compared to other emission ratios found in the literature.

For comparison with previous studies, our corrected enhancement ratios (i.e., equivalent emission ratios) have been converted into equivalent emission factors using Equation 1. In order to compare our results with others, a representative dataset of EF_x has been selected, including ground-based (Griffin et al., 2013; Paton-Walsh et al., 2005), satellite (Tereszczuk et al., 2012; Rinsland et al., 2007) and aircraft (Le Breton et al., 2013; Lewis et al., 2013; Simpson et al., 2011; Goode et al., 2000) measurements, as well as compilations of numerous data (Akagi et al., 2011; Andreae and Merlet, 2001) for boreal and extratropical forests. The two latter studies contain a comprehensive set of emission factors from the burning of numerous vegetation types derived from various measurement platforms. The $EF_{C_2H_6}$ and EF_{HCN} from Akagi et al. (2011) have been estimated from a combination of ground-based in situ (with a mean value of $EF_{C_2H_6} = 3.0 \pm 2.3 \text{ g kg}^{-1}$ and $EF_{HCN} = 2.5 \pm 1.5 \text{ g kg}^{-1}$) and airborne measurements (with a mean value of $EF_{C_2H_6} = 0.6 \pm 0.3 \text{ g kg}^{-1}$ and $EF_{HCN} = 0.9 \pm 0.3 \text{ g kg}^{-1}$). Their reported standard deviations represent variability between studies whereas they are from the 1-sigma uncertainty propagation for the single studies listed in Table 1. In addition, because in those studies, different values of EF_{CO} were used to calculate EF_x , ER_x is also reported when available (Table 1). Our equivalent $ER_{C_2H_6}$ (0.0108 ± 0.0036) is higher than values found in the literature, that is consistent with the fact that fires emits more Non-Methane Hydrocarbons than previously thought (Akagi et al., 2011). However, even if our value is in good agreement with ground-based and satellite measurements reported by Griffin et al. (2013) and Rinsland et al. (2007), it is higher than emission ratios derived from aircraft measurements as reported by Lewis et al. (2013), Simpson et al. (2011), and Goode et al. (2000). This may be due to potential biases in the measurement

techniques and/or the different geometry employed in the sampling that biases the measurements to one stage of burning over another, e.g. aircraft are measuring over a certain altitude range, which might be biased toward flaming combustion often injected into the upper troposphere, whereas a ground-based FTIR measures the total columns from the surface, which might be biased toward smoldering combustion (Hurst et al., 1994)). But because this pattern is not seen when comparing our ER_{HCN} with others, the reason for our high value of $ER_{C_2H_6}$ is not clear yet and these discrepancies may reflect the natural variability of the emissions. Indeed, our equivalent ER_{HCN} (0.0054 ± 0.0022) lies within the range of all other values.

The emission factors of C_2H_6 calculated in this study are $1.47 \pm 0.50 \text{ g kg}^{-1}$ when considering the EF_{CO} value from Akagi et al. (2011) and $1.24 \pm 0.44 \text{ g kg}^{-1}$ when considering the EF_{CO} value from Andreae and Merlet (2001). Those values are in excellent agreement with the value reported by Griffin et al. (2013), and agree well with satellite measurements in Rinsland et al. (2007), and the mean for boreal forest fires found in Akagi et al. (2011) (see Table 1). However, our values of $EF_{C_2H_6}$ are at least five times higher than $EF_{C_2H_6}$ for Australian temperate forest calculated from ground-based FTIR measurements because the fuel in Australia is different and this vegetation (predominantly Eucalyptus trees) has low biomass burning emissions of C_2H_6 (Paton-Walsh et al., 2005).

For HCN, emission factors of $0.66 \pm 0.27 \text{ g kg}^{-1}$ and $0.56 \pm 0.21 \text{ g kg}^{-1}$ (using EF_{CO} value from Akagi et al. (2011) and Andreae and Merlet (2001), respectively) have been calculated in this study (Table 1), which agrees within combined errors with all previous studies referenced here, except for that of Rinsland et al. (2007). Rinsland et al. (2007) calculated an EF_{HCN} of around five times lower than that derived from laboratory measurements of boreal fuels of 0.92 g kg^{-1} reported by Bertschi et al. (2003), which is not in agreement with the mean for boreal forest fires

found in Akagi et al. (2011). This low value may partially be attributed to the relatively low EF_{CO} of $86 \pm 17 \text{ g kg}^{-1}$ (derived from the mean of airborne measurements from an Alaskan wildfires reported in Nance et al. (1993) and Goode et al. (2000)) used in Rinsland et al. (2007) study to estimate EF_{HCN}. In addition, a recent study provided ER_{HCN} for very different but globally important fuel types (Akagi et al., 2013, Figure 10) and highlighted that ER_{HCN} has a high fuel dependence, ranging from below detection for pure wood in cooking fires (Christian et al., 2010) to 3% or greater for some peat samples (Akagi et al., 2011). However, the mean ER_{HCN} reported in Akagi et al. (2013) ranges between 0.0063 and 0.0095 which agrees well, within the uncertainties, with our ER_{HCN}.

5) Conclusions

In this study, we used ground-based FTIR measurements of biomass burning products (CO, HCN, and C₂H₆) made in the high Arctic, in order to assess emission ratios relative to CO for the boreal forest. With several independent sources of information (AODs, HYSPLIT back-trajectories, MODIS images, OMI aerosol index, and IASI CO total columns), we confirmed that the FTIR measurements recorded in August 2010 were inside a persistent smoke plume transported from Russia. The equivalent emission factor of C₂H₆ ($1.47 \pm 0.50 \text{ g kg}^{-1}$) found here is in agreement with the mean values reported in the compilation studies of Akagi et al. (2011) and Andreae and Merlet (2001), with the satellite measurements of Rinsland et al. (2007), and with the ground-based measurements of Griffin et al. (2013) for boreal forest. However, our emission factor of C₂H₆ are found to be higher than values derived from airborne observations (Simpson et al., 2011; Goode et al., 2000), possibly due to the different sampling method. Also the low emission factor value derived from ground-based observations (Paton-Walsh et al., 2005) might be due to the different type of fuel burned in Australia. Our equivalent emission factor of HCN

($0.66 \pm 0.27 \text{ g kg}^{-1}$) is in agreement with all studies referenced here (Akagi et al., 2011; Andreae and Merlet, 2001; Simpson et al., 2011; Paton-Walsh et al., 2005), with the exception of Rinsland et al. (2007), who reported a lower value that might describe the real variability of HCN emission (Akagi et al., 2013). Given the large range of values found in the literature, these new measurements add new observations to the sparse dataset of emission factors that have been reported and compiled in the literature. Future work will focus on the detection of other fire events, as well as retrieval of other trace gases from smoke spectra recorded at Eureka.

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445 **Table 1:** Emission factors (g kg^{-1}) and emission ratios for C_2H_6 and HCN calculated in this study
 446 alongside those found in the literature.

	platform	vegetation type	EF_{CO}^1	ER_x		EF_x	
				C_2H_6	HCN	C_2H_6	HCN
This study	ground-based ^a	<i>boreal</i>	127 ± 45	0.0108 ± 0.0036	0.0054 ± 0.0022	1.47 ± 0.50	0.66 ± 0.27
		<i>extratropical</i>	107 ± 37			1.24 ± 0.44	0.56 ± 0.21
Akagi et al. (2011)	compilation	<i>boreal</i>	127 ± 45	n/a	n/a	1.79 ± 1.14	1.52 ± 0.81
Andreae and Merlet (2001)	compilation	<i>extratropical</i>	107 ± 37	n/a	n/a	$0.73 \pm 0.41^*$	0.81^*
Le Breton et al. (2013)	aircraft ^b	<i>boreal</i>	n/a	n/a	0.0038 ± 0.0002	n/a	n/a
Lewis et al. (2013)	aircraft ^b	<i>boreal</i>	n/a	0.0051 ± 0.0035	n/a	n/a	n/a
Simpson et al. (2011)	aircraft ^c	<i>boreal</i>	113 ± 72	0.0046 ± 0.0090	0.0082 ± 0.0020	0.56 ± 0.13	0.89 ± 0.29
Goode et al. (2000)	aircraft ^d	<i>boreal</i>	88.8	0.0073	0.0069	0.66	0.61
Rinsland et al. (2007)	satellite ^e	<i>boreal</i>	86 ± 17	0.0098 ± 0.0008	0.0024 ± 0.0003	0.91 ± 0.19	0.20 ± 0.05
Tereszchuk et al. (2012)	satellite ^b	<i>boreal</i>	n/a	0.0069 ± 0.0023	0.0027 ± 0.0018	n/a	n/a
Griffin et al. (2013)	ground-based ^b	<i>boreal</i>	122 ± 45	0.0100 ± 0.0060	n/a	1.35 ± 0.51	n/a
Paton-Walsh et al. (2005)	ground-based ^f	<i>temperate</i>	107 ± 37	0.0023 ± 0.0005	0.0042 ± 0.0016	0.26 ± 0.11	0.43 ± 0.22

¹ Used to convert ER_x to EF_x (g kg^{-1})

* updates from M. O. Andreae (see Paton-Walsh et al., 2005)

^a Fire from Russia, measurements made in the Arctic region (PEARL, 80.05°N, Eureka)

^b Fire from Canada, measurements made over Northwestern Ontario Canada (BORTAS campaign)

^c Fire from Canada, measurements made over Canada (ARCTAS campaign)

^d Fire from Alaska, measurements over Alaska

^e Fire from Alaska and Western Canada, measurements over Alaska and Canada (between 50.2°N and 67.8°N)

^f Fire from Australian temperate forest, measurements at Wollongong (Australia, 35.5°S)

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Figure 1: Trace gas total columns and AODs measured at PEARL in August 2010.

(a) Time series of FTIR total columns of CO (from TCCON in blue and NDACC in cyan), HCN (in red, scaled by a factor of 1.7) and C₂H₆ (in green) from the 9th to 30th of August 2010. Error bars are the total column uncertainties of 2.5% (and 2%), 9.0%, and 3.5% for CO (and TCCON CO), HCN, and C₂H₆ respectively. The 23rd August 2010 is indicated by the yellow box. (b) Time series of CO total columns (FTIR measurements in blue: TCCON in blue and NDACC in cyan) and total, fine and coarse mode AODs at 500 nm derived from AERONET (in black, red and dark blue, respectively) plotted for the 23rd August 2010. (c) Distribution of CO total columns measured by IASI within 550 km around Eureka (indicated by black box) for the same day.

Figure 3: FTIR total columns of C_2H_6 and HCN plotted against CO total columns. (a) C_2H_6 versus CO for all of 2010 (black) and for August 2010 (red). (b) Correlation plots of C_2H_6 versus CO for August 2010. (c) HCN versus CO for all of 2010 (black) and for August 2010 (red). (d) Correlation plots of HCN versus CO for August 2010. The error bars represent the total uncertainties of the retrievals.