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Indoor air pollution from burning yak dung as a household fuel in Tibet

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HIGHLIGHTS

- Real-time BC and $PM_{2.5}$ concentrations were measured in households in Nam Co, Tibet.
- 23 households were surveyed on energy use and awareness of indoor air pollution.
- Chimney installation may not by itself ensure adequate indoor air quality.
- We observed a lower BC/$PM_{2.5}$ ratio for dung combustion than previous estimates.
- About 0.4–1.7 Gg/year of additional BC is emitted by yak dung combustion in Tibet.

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ABSTRACT

Yak dung is widely used for cooking and heating in Tibet. We measured real-time concentrations of black carbon (BC) and fine particulate matter with an aerodynamic diameter of 2.5 μm or less ($PM_{2.5}$) emitted by yak dung burning in six households with different living conditions and stove types in the Nam Co region, Tibet. We observed a much lower average BC/$PM_{2.5}$ mass ratio (0.013, range 0.006–0.028) from dung combustion in this area than previously reported estimates, ranging between 0.05 and 0.11. Based on our measurements, estimated fuel use, and published emission factors of BC and $PM_{2.5}$, about 0.4–1.7 Gg/year of BC is emitted by yak dung combustion in Tibet in addition to the previously estimated 0.70 Gg/year of BC for Tibetan residential sources. Our survey shows that most residents were aware of adverse health impacts of indoor yak dung combustion and approximately 2/3 of residents had already installed chimney stoves to mitigate indoor air pollution. However, our measurements reveal that, without adequate ventilation, installing a chimney may not ensure good indoor air quality. For instance, the 6-h average BC and $PM_{2.5}$ concentrations in a stone house using a chimney stove were 24.5 and 873 μg/m^3, respectively. We also observed a change in the BC/$PM_{2.5}$ ratios before and after a snow event. The impact of dung moisture content on combustion efficiency and pollutant emissions needs further investigation.

1. Introduction

Tibet is one of the most remote areas in the world and is considered one of the cleanest regions (Kang et al., 2009). Past measurements of average ambient black carbon (BC) and fine particulate matter with an aerodynamic diameter of 2.5 μm or less ($PM_{2.5}$) concentrations show 82 ng/m^3 and 2–3 μg/m^3, respectively, in Nam Co, a pastoral region in Tibet (Fig. 1) (Chen et al., 2011; Ming et al., 2010). However, indoor air pollution due to domestic biomass combustion is severe. Most residents in pastoral counties in Tibet still follow traditional nomadic lifestyles (Li et al., 2012a). With fossil fuel priced beyond their means and limited economic

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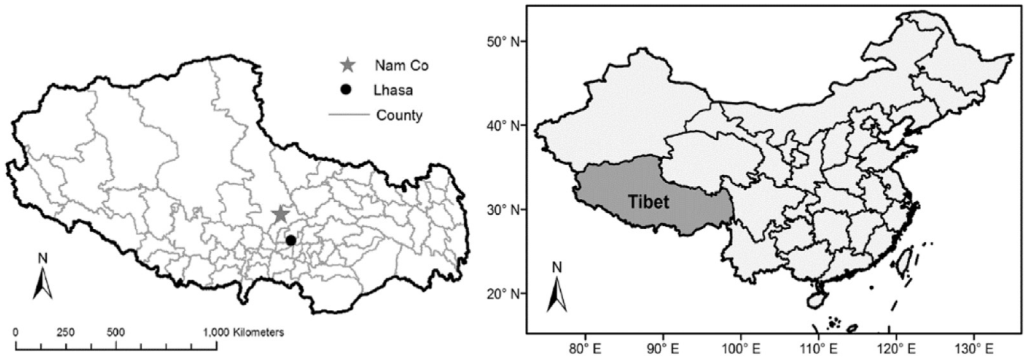

Fig. 1. Map locating the study site in Nam Co, Tibet, China.

opportunity, rural Tibetan households consume large amounts of local biomass, especially yak dung, for cooking and heating. In fact, biomass energy accounts for almost 70% of the total household energy consumption and yak dung alone accounts for more than half of residents' domestic energy consumption in this region (Gao et al., 2009; Kang et al., 2009; Liu et al., 2008).

Biomass combustion releases many air pollutants. Among them, particulate matter (PM), especially smaller PM such as $PM_{2.5}$ is noted for its association with adverse health impacts such as cardiovascular disease, respiratory disorders, and cancers (Pope and Dockery, 2006). In addition to health effects, the particles released by combustion have major climate impacts. BC, for example, is one of the largest contributors to global warming and has especially large effects in regions where the emissions are the strongest (Menon et al., 2002; Ramanathan and Carmichael, 2008). Some models indicate that BC accelerates the decrease of snow/ice cover in the Himalayan–Tibetan region and that it affects the large-scale atmospheric circulation and hydrologic cycle (Menon et al., 2002, 2010). BC is therefore often considered as a target for reducing both air pollution and near-term climate impacts, and controlling cookstove emissions is one proposed way to achieve co-benefits (Andreae and Ramanathan, 2013).

Previous studies have measured several pollutants in tents in Nam Co, Tibet. In a household using a simple stove without a chimney, the 24-h average concentrations of $PM_{2.5}$ ranged between 1270 and 1670 $\mu g/m^3$ (Chen et al., 2011; Kang et al., 2009; Li et al., 2012a, 2012b). A tent with a chimney stove had a lower 24-h average $PM_{2.5}$ concentration of 97 $\mu g/m^3$ (Chen et al., 2011), which was still approximately four-times higher than the WHO Air Quality Guideline (25 $\mu g/m^3$, 24-h mean). While previous studies measured total $PM_{2.5}$ from biomass combustion in Tibetan tents, no study quantified the BC component. Moreover, all previous studies were conducted in the summer, which is the warmest season in Tibet (monthly average temperature in August was 8.8 °C in Nam Co in 2005) (You et al., 2007). During winter or spring when the temperature is much lower (monthly average temperature in March, for example, was −5.5 °C in Nam Co in 2006) (You et al., 2007), more severe indoor air pollution is possible due to increased heating demands.

This study monitored the indoor air pollutants BC and $PM_{2.5}$ in six local households with different living conditions and stove types in Nam Co in March 2013. A survey about residents' energy use, stove operation, daily activities, and other related topics, was also conducted in 23 local households. We present average indoor pollutant levels, the BC/$PM_{2.5}$ mass emission ratio, new regional BC emissions estimates from residential combustion in Tibet, and some important case study observations regarding the impact of living environment on indoor air pollution.

2. Methodology

2.1. Study site

This study took place in the Nam Co region (30.460° N, 90.580° E, 4730m a.s.l.), a pastoral area in the southern Tibetan Plateau between March 17–23, 2013 (Fig. 1). During the study period, the average daily temperatures and precipitation were −6 °C and 2.3 mm, respectively. There were 4291 residents and 751 households registered in Nam Co in the 2000 census. Yak and sheep herding is the major occupation of most local households, and most residents follow a traditional nomadic lifestyle (Li et al., 2012a). However, about 5% of the residents also derive income from tourism.

Residents live in different types of tents/houses in the study area (Supplementary Materials S1 and S2). Both tents and houses have only one room without a separate kitchen, and people sleep, eat, and cook in the same room. Two types of tents and biomass stoves are used in this region (Kang et al., 2009; Li et al., 2012a). Briefly, traditional tents (23.2 m^3) and advanced tents (38.5 m^3) have similar structure and air ventilation conditions, but the fabric and volume differ. Simple stoves without chimneys and chimney stoves are used for both cooking and heating in this region. Simple stoves are iron circles, each of which is supported by three iron bars (50 cm in height and 40 cm in diameter). A hole (1×0.5 m^2) on top of the tent ventilates smoke from simple stoves. Chimney stoves are made of thin iron sheets, and feature a combustion chamber (40 cm in height and 40 cm in diameter), a plenum channel ($15 \times 18 \times 60$ cm^3), and a chimney (2.2 m in height and 16 cm in diameter). Yak dung is the only biomass fuel used in tents or houses in this region.

2.2. Survey procedure

The survey was designed to collect information on energy use, daily activities of household members, residents' awareness of indoor air pollution and its adverse health impacts, and their willingness to pay for indoor air pollution mitigation. Eligible subjects were residents of a typical nomadic household in Nam Co that gave oral consent to participate. Interviews took place on March 17, 18, 20, and 21, 2013 in Nam Co, in response to consent from 23 households. The survey included residents living in different tents/houses with diverse socioeconomic status and stove types. Business establishments (i.e., restaurants) and institutional settings (i.e., police services) were not included. A local resident who works as a driver and translator between Mandarin and Tibetan assisted with interviews. Questions were read to consenting, adult subjects and the responses were recorded, coded and analyzed. Survey questions are included in the Supplementary Material S3.

2.3. Aerosol instruments

BC concentrations were measured by a Model AE51 microAeth Black Carbon aerosol monitor (Aethlabs, Inc., range: 0–1 mg/m^3, resolution: 0.001 μg/m^3) at 50 mL/min flow rate. Due to the high concentrations of BC in the residences, the filter was changed every 2–4 h. The battery was recharged overnight every day. $PM_{2.5}$ concentrations were measured with a Model 8520 DustTrak aerosol monitor (TSI, range: 0.01–100 mg/m^3, resolution: 0.1% of reading or 0.001 mg/m^3) at 1.7 L/min flow rate. Two sets of batteries were used and recharged every day and the $PM_{2.5}$ instrument was left operating overnight in residents' homes. Operation temperatures for the BC and $PM_{2.5}$ monitors are 0–40 °C and 0–50 °C, respectively. Because of occasional battery failure due to cold, and the need to change filters every 2–4 h while respecting residents' privacy, it was not possible to monitor BC for 24 h, but four overnight $PM_{2.5}$ datasets were successfully collected in this study. The instruments were calibrated once before starting measurements.

2.4. Aerosol sampling strategy

To monitor air pollution in different relevant living environments with various types of stoves, we selected households with construction and stove characteristics that were typical of the study area. Participation was voluntary. Three traditional tents, one advanced tent, one stone house, and one simple house were selected for measurement of indoor BC and $PM_{2.5}$ concentrations. Each household was measured on separate days for 9.8 and 17 h, on average, for BC and for $PM_{2.5}$, respectively.

Since inhabitants spend much time sitting on the ground around the stove, which is put in the middle of the tent/house, we chose a sampling site close to their breathing zone. The BC and $PM_{2.5}$ monitors were placed approximately 0.5 m above the ground and 1 m horizontally away from the stove. Generally, residents get up around 7 am, light the stove, and cook breakfast. Men, rarely women, leave the tent/house and start herding sheep and yak around 10 am. Lunch is prepared around noon and dinner around 7 pm. The stove is then used mainly for heating and boiling until around 11 pm, when residents go to bed (Chen et al., 2011). Fuels are added every 15–20 min while the stove is lit, and more frequently when cooking. The start and end times of the measurement period at each household varied depending on several logistical reasons.

2.5. Aerosol data processing

Smoothing was conducted for the BC and $PM_{2.5}$ real-time data by averaging the value at each time point with the two adjacent points before and after (a moving five-point average). The ventilation of each household was estimated as the time for $PM_{2.5}$ concentrations to decrease from 200 μg/m^3 to below 10 μg/m^3 after the fire was extinguished. We analyzed BC and $PM_{2.5}$ concentrations for the entire measurement period and the 6-h period between 11:40 am and 5:40 pm in each household. This 6-h period was the time that was successfully monitored in all households despite logistical challenges and included cooking lunch and other major activities within tents. The 6-h data enabled nominally more direct comparisons between households.

Table 1
Living conditions of residents in the study area.

Variable	Number (%)
Live in a tent	12 (52.2)
Have a simple stove without a chimney	7 (30.4)
Only use yak dung for cookstoves	19 (82.6)
Annual median income	5500 RMB (US$890)
Average hours stove is used per day	16 ± 1.3
Average number of residents in a households	6 ± 1.7

3. Results

3.1. Survey results: energy use, living conditions and stove types in Nam Co

Table 1 summarizes key survey results. Most of the respondents lived in tents and more than 2/3 used chimney stoves. As in earlier work in Nam Co (Chen et al. (2011)), these households (on average) used stoves for 16 h a day, and on average had 6 residents.

Yak dung was the main fuel for cooking and the only fuel for heating. Only 4 households (17%) sometimes used liquefied petroleum gas (LPG) for cooking and their annual incomes were all at or above 10,000 RMB (US$1631), almost twice the median annual income (5500 RMB, US$890) of local households. Socioeconomic status affected the stove-type residents used. Fig. 2 shows the percentage of households using simple or chimney stoves relative to the total number of households in each of the four annual income ranks. More than one-third of the households with an annual income under 2000 RMB (US$324) used simple stoves without chimneys. As income increased, that fraction decreased, and all households with annual income above 20,000 RMB (US$3238) used chimney stoves. The point-biserial correlation coefficient between stove-type and income is 0.46. In most cases, households without chimney stoves were interested in using chimney stoves, but did not for economic reasons. Their willingness to pay for a chimney was 120 RMB (US$19.4) on average, which is substantially lower than the current price of above 350 RMB (US$56.7).

74% of surveyed residents were aware of negative impacts of indoor air pollution on their health and reported varying levels of discomfort when using stoves, including cough or eye and nose/throat irritation (Fig. 3, left). For some residents, reducing adverse health impacts was the main reason for switching to a chimney stove. In comparison to households without a chimney, a larger percentage of households using chimney stoves (75%) reported that

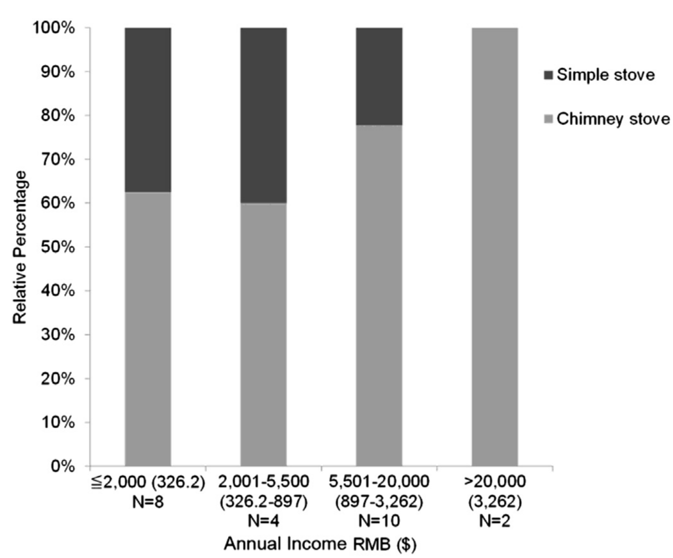

Fig. 2. Stove-type used, grouped by annual household income. The number of households in each category is shown on the x-axis.

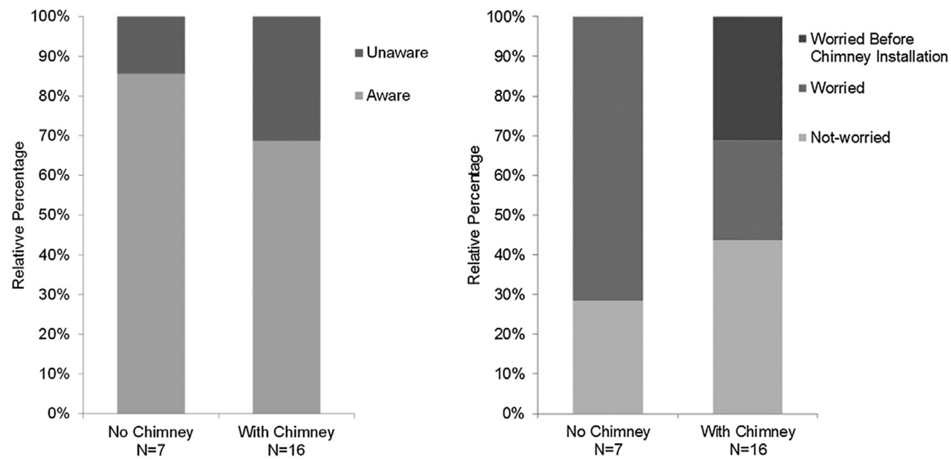

Fig. 3. Left, awareness of adverse health impacts from burning fuel indoors relative to residents' stove type. Right, percentage of residents worried about their health consequences due to indoor stove usage relative to residents' stove type.

they were not worried about their health (after installing a chimney), as opposed to only 29% of those using simple stoves (Fig. 3, right).

3.2. Daily variation, peak, and average air pollutant concentrations in different households

Fig. 4 shows the real-time air pollution data we collected on March 22 in a traditional tent with a chimney, illustrating the variation of indoor air pollutant concentrations in a day. The peak air pollutant concentrations were related to cooking activities and addition of fuel, and BC and $PM_{2.5}$ concentrations were fairly well correlated with each other.

Table 2 summarizes the measurement results in different households and shows that the average concentrations of BC and $PM_{2.5}$ during each day's entire measurement period (Table 2, the last two rows) were similar to averages and ratios during the 6-h sampling period (11:40 am–5:40 pm) (Table 2, the 7th and 8th rows). Thus, comparing household or stove types is so far more limited by the amount of household specific sampling than the time period employed. The 6-h average BC and $PM_{2.5}$ concentrations in each household ranged from 0.52–24.48 $\mu g/m^3$ and 42.95–1530 $\mu g/m^3$, respectively. The average $BC/PM_{2.5}$ ratio measured in this study (based on 6-h data) was 0.013, ranging between 0.006 and 0.028, and the correlation coefficient of BC and $PM_{2.5}$ concentrations during the 6-h similarly ranged between 0.31 and 0.95. The peak values observed from each 6-h period are shown in Fig. 5.

4. Discussion

4.1. Indoor air pollution in Nam Co and in other regions

Approximately 2.7 billion people burn biomass (wood, animal dung, crop waste) around the world (WHO, 2007). Compared with results reported by some studies in households without chimneys in other areas, we find that the air pollutant concentrations in Tibetan households are higher. For households using a simple stove, the average $PM_{2.5}$ concentration during our entire study period was 956 $\mu g/m^3$. Mukhopadhyay et al. (2012) conducted measurements in five rural households using biomass as fuel in Haryana, India, and found the 24-h mean $PM_{2.5}$ concentrations to be 468 $\mu g/m^3$. Balakrishnan et al. (2004) reported that the 24-h average concentrations of respirable particulates based on 83 households using dung as fuel in India were 732 ± 88 $\mu g/m^3$. In Mexico, $PM_{2.5}$ concentrations in a kitchen using biomass as fuel were 554.7 ± 492.9 $\mu g/m^3$ (Brauer et al., 1996).

The higher average indoor air pollution we found in Tibet may be partly because of its high altitude and relatively low temperature. The low annual temperatures increase demand for household heating, resulting in longer heating times. Residents naturally use stoves and stay inside longer than in other regions. Stove operation time in Tibetan households was 16 h, on average, and up to 17.5 h per day, compared to, for example, 2–5 h in India (Balakrishnan et al., 2004; Mukhopadhyay et al., 2012). Similarly, very high pollution levels have been reported in other high altitude areas. In a Bolivian highland village Cantuyo (4100 m a.s.l), residents used cow dung as their main fuel and traditional stoves for cooking and heating. Indoor average PM_{10} concentrations were 3690 ± 5380 $\mu g/m^3$ (Albalak et al., 1999). Based on the $PM_{2.5}/PM_{10}$ ratio of 0.8 from biomass combustion reported elsewhere (Artaxo et al., 1998; Reid et al., 2005), the estimated $PM_{2.5}$ concentrations in Cantuyo households were approximately 2952 $\mu g/m^3$, which is even higher than values we measured in traditional tents in Tibet. Davidson et al. (1986) also reported high daily-average hours of stove use and very high indoor air pollution during the winter in Nepal with total suspended particulate (TSP) values of 8800 $\mu g/m^3$. These high air pollutant concentrations in Tibetan households, together with long hours spent indoors, raise concerns of high air pollution exposure.

4.2. Estimates of the $BC/PM_{2.5}$ ratio and regional BC emissions from yak dung combustion

We observed that there was a large range in the correlation coefficient of BC and $PM_{2.5}$ (0.31–0.95) (Table 2), as well as in the $BC/PM_{2.5}$ ratio (0.006–0.028). Various combustion conditions due to different stove types, human activities (cooking and adding fuels), and moisture content of fuel most likely have led to this result. A previous study reports that chimney stoves and simple stoves differ in air supply to the fuel and heat transfer rate, which leads to different combustion conditions (MacCarty et al., 2010). We also found evidence that the air circulation within households was different depending on the existence of a chimney and construction of the tent/house, which could affect the observed values at the sampling site. Moreover, we observed a change in combustion from smoldering to flaming after residents added fuel and vice versa when the fuel was burning out. Additionally, we found from our

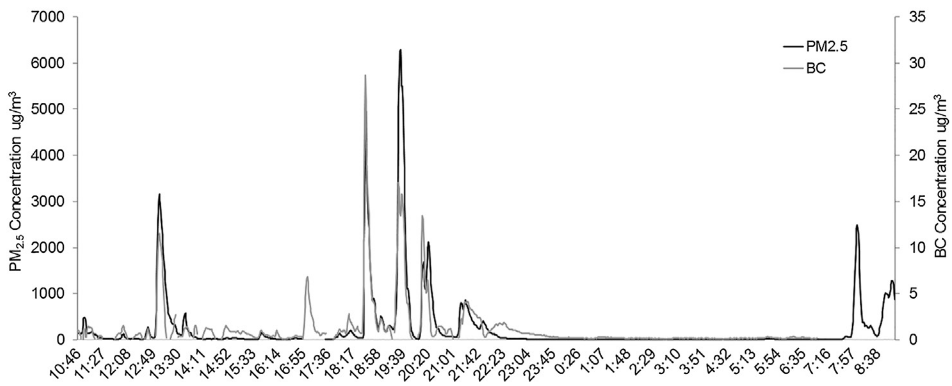

Fig. 4. Continuous air pollutant concentrations in a traditional tent with a chimney stove, on March 22.

measurements that the moisture content of yak dung also likely plays an important role in determining combustion conditions (Yang et al., 2003). Tibetan residents collected yak dung in a pile and left it uncovered in the sun to dry. Thus, some dung was not completely dried before it was burned and precipitation may have significantly increased the moisture content of dung.

The average 6-h BC/$PM_{2.5}$ ratio measured in this study, 0.013, is lower than the previously reported BC/$PM_{2.5}$ or BC/total carbon (TC) ratios, which varied from 0.05 to 0.11 (Supplementary Material S4). Our lower BC/$PM_{2.5}$ ratio suggests relatively more smoldering combustion. Possible causes include higher fuel moisture content and the lower atmospheric pressure at high elevation (Li et al., 2009). Our BC/$PM_{2.5}$ ratio for dung combustion combined with the TC or $PM_{2.5}$ emission factors reported by previous studies (Supplementary Material S4) can be used to calculate a range of BC emission factors for dung fires between 0.03 g/kg (based on our average BC/$PM_{2.5}$ ratio of 0.013 and the minimum TC emission factor of 2.56 g/kg (Venkataraman et al., 2005)) and 0.30 g/kg (based on our average BC/$PM_{2.5}$ ratio of 0.013 and the maximum TC emission factor of 22.9 g/kg (Keene et al., 2006)). We find reasonable agreement with the previously reported BC emission factor estimates from dung combustion: 0.12 (Venkataraman et al., 2005), 0.25 (Reddy and Venkataraman, 2002), and 0.49 (Saud et al., 2012).

To estimate regional emissions from yak dung burning, we used the average per capita yak dung consumption of approximately 1640 kg/year (Liu et al., 2008). This per capita biofuel use is considerably higher than the global average, most likely due to the cold climate and high heating needs (Yevich and Logan, 2003). Combining this per capita yak dung consumption with the 2000 population census data of 4291 residents in Nam Co, approximately 7 kt/year of yak dung is consumed in the region. Coupling this value with emission factors previously reported from different experiments, several estimates of BC and $PM_{2.5}$ emissions from Nam Co in 2000 can be derived: 1) 0.84 Mg/year BC and 18 Mg/year $PM_{2.5}$ based on the emission factor of BC and TC as 0.12 and 2.56 g/kg, respectively (Venkataraman et al., 2005); 2) 2.1 Mg/year BC and 160 Mg/year $PM_{2.5}$ based on 22.9 gC/kg fuel (Keene et al., 2006) and our average BC/$PM_{2.5}$ ratio 0.013; and 3) 3.4 Mg/year BC and 31 Mg/year $PM_{2.5}$ based on the emission factor of BC and TC as 0.49 and 4.36 g/kg, respectively (Saud et al., 2012). Residential BC and $PM_{2.5}$ emissions in Tibet were estimated to be 0.695 and 3.46 Gg/year in 2000, respectively, without including emissions from yak dung burning (Kurokawa et al., 2013). Since Nam Co only holds 0.2% of the rural population in Tibet based on the Tibet Statistical Yearbook 2012 and assuming 0.8–3.4 Mg/year of BC and 18–160 Mg/year of $PM_{2.5}$ from the residences in Nam Co, it is likely that another 0.4–1.7 Gg/year of additional BC and 9–80 Gg/year of $PM_{2.5}$ emissions have been unaccounted for in their estimate.

4.3. Impact of stove types and other factors on indoor air pollution

In our study, the average 6-h $PM_{2.5}$ and BC concentrations in two tents using simple stoves were 6.5 and 10 times higher, respectively, than in two tents using chimney stoves. This is consistent with the previous results that chimneys decrease the indoor air pollutant concentrations (Chen et al., 2011; Li et al., 2012a). However, our measurements include an important case showing that simply installing a chimney may not be, by itself, a sufficient mitigation measure in some living environments. For example, in the stone house using a chimney stove, the indoor air pollution was still severe and the 6-h average BC and $PM_{2.5}$ concentrations were the highest and the third highest among the 6 households, respectively. The 6-h average $PM_{2.5}$ concentrations in households only using yak dung as heating and cooking fuels in: 1) tents without chimneys; 2) tents with chimneys; and 3) a stone house with a chimney were 1243, 191, and 873 $\mu g/m^3$, respectively, and BC concentrations for the same groups were 13.3, 1.31, and 24.5 $\mu g/m^3$, respectively. Fig. 5 shows the magnitude of the high 6-h peak BC concentrations measured in the stone house on March 18.

Several reasons potentially explain this. Ventilation of houses could be somewhat limited if residents close windows and doors to stay warm and save fuel. We estimated the air exchange rate in the different households (Table 2). In tents that use simple stoves and have a hole on top, the $PM_{2.5}$ concentrations dropped the fastest (14.0 $\mu g/m^3$/min) after the fire was extinguished among all the households. In contrast, the $PM_{2.5}$ exchange rate in the simple house (ID 6 in Table 2) at night when the door was closed was the lowest in this study (1.56 $\mu g/m^3$/min). This low exchange rate does not reflect the ventilation of this household during daytime when the door was open, but it provides an indication that the ventilation of the stone house may have been similarly limited. Maintaining ventilation even with a chimney is important because the chimney cannot ventilate emissions introduced to the living area when, for example, fuel is added or lighting the stove. Our survey showed that a larger percentage of households using chimney stoves (75%) were not worried about their health after installing a chimney (Fig. 3, right), but our data show that installing a chimney may not be a sufficient mitigation measure in a house. Residents living in one house with a chimney were still exposed to severe indoor air pollution.

The lowest average BC and $PM_{2.5}$ concentrations were measured in a simple house with a chimney stove (ID 6 in Table 2). This household lived on tourism and used LPG for cooking. They kept their door open all day to serve tourists leading to greater ventilation and their higher income made it possible to use LPG for cooking. LPG is more expensive than yak dung, but burns with lower emission factors for BC and PM pollutants. For example, the

Table 2
Summary of Measurements in six local households.

ID	1	2	3	4	5	6
Measured date	March 17	March 20	March 22	March 19	March 18	March 21
Household[a]	Trad. Tent	Trad. Tent	Trad. Tent	Adv. Tent	Stone House	Simple House
Number of family members	8	7	8	5	8	5
Chimney	No	No	Yes	Yes	Yes	Yes
Using gas for cooking	No	No	No	No	No	Yes
$PM_{2.5}$ exchange rate (μg/m^3/min)	18.9	9.15	2.89	7.79	–	1.56
BC concentrations during 6 h Avg. (Min. - Max.) μg/m^3	18.2 (0.41 −127)	8.45 (0.05 −63.8)	1.18 (0.04 −11.5)	1.43 (0.05 −9.59)	24.5 (0.01 −463)	0.52 (0.02 −4.14)
$PM_{2.5}$ Concentrations during 6 h Avg. (Min.– Max.) μg/m^3	957 (30.0 −8590)	1530 (7.40 −22500)	178 (5.60 −3150)	204 (7.20 −1340)	873 (7.00 −9880)	43 (6.80 −570)
6 h Average BC/$PM_{2.5}$ Ratio	0.019	0.006	0.007	0.007	0.028	0.012
6 h Correlation coefficient of BC and $PM_{2.5}$ concentrations	0.47	0.86	0.95	0.41	0.81	0.31
BC Concentrations Avg.[b] (Min. - Max.) μg/m^3	16.5 (0.41 −127)	7.71 (0.05 −63.8)	1.25 (0.02 −28.7)	2.48 (0.05 −25.0)	19.1 (0.01 −463)	0.67 (0.02 −5.83)
$PM_{2.5}$ concentrations Avg.[b] (Min. - Max.) μg/m^3	633 (3.00 −8590)	1280 (1.00 −38200)	241 (2.20 −6290)	593 (1.00 −10900)	693 (6.20 −9880)	56.5 (0.00 −1290)

[a] Trad. Tent: Traditional Tent; Adv. Tent: Advanced Tent.
[b] Based on measurements during the entire measurement period.

reported emission factors of BC for cow manure combustion are 0.12–0.49 (Supplementary Material S4), while the same values for LPG are approximately 0.01 g/kg (Venkataraman et al., 2005). The use of LPG and greater ventilation most likely led to much lower BC and $PM_{2.5}$ concentrations than those in the advanced tent with a chimney, which recorded the second lowest concentrations among the measured households.

It is of interest that the second tent (ID 2 in Table 2) had less than half the average BC concentration, but 1.6 times higher average $PM_{2.5}$ concentration and a 3.7 times lower BC/$PM_{2.5}$ ratio than the first tent (ID 1 in Table 2), despite being the same stove and tent type (simple stove, traditional tent). This is likely due to different moisture contents of yak dung on those two days. As discussed before, residents left yak dung uncovered in the sun and the snow event during the night of March 19 could have resulted in higher moisture content of the dung on the following day (March 20). This may have led to increased smoldering combustion on March 20 compared to March 17, which would cause higher $PM_{2.5}$ and organic carbon production, but less BC because of relatively less flaming (Christian et al., 2003; Smith, 1987). These results demonstrate the need for more investigation on the impact of dung moisture content on combustion efficiency, as well as the difficulty of reducing both BC and $PM_{2.5}$ emissions per unit fuel used simultaneously.

4.4. Future study directions

Our study provides the first indoor BC measurements in Tibet and also the first $PM_{2.5}$ measurements in the non-summer season. Air pollutant concentrations measured in this study and the average hours of stove use are comparable to those reported by previous studies, which were conducted in summer (Chen et al., 2011; Li et al., 2012a, 2012b). Thus, there is no indication that indoor air pollution in Tibet varies greatly by season. Moreover, we observed a much lower BC/$PM_{2.5}$ ratio (0.013, ranging between 0.006 and 0.028) from dung combustion in Tibet than in previous studies of dung combustion carried out elsewhere. We estimate that 0.4–1.7 Gg/year additional BC and 9–80 Gg/year additional $PM_{2.5}$ emissions from yak dung combustion occur in Tibet that is not recognized in existing inventories. Yak dung combustion is a significant regional source of BC and $PM_{2.5}$ and our study helps call attention to the higher fuel use, more serious indoor air pollution, and likely larger per capita regional emissions that increasingly seem typical of third world households at higher elevations where heating needs can be much greater year-round than in tropical areas. Finally, our study indicates that installing a chimney may not necessarily solve air pollution problems. Ventilation is also a key factor and attempts to reduce fuel costs by reducing ventilation can also reduce indoor air quality.

Our study also has limitations, e.g. relatively small sample size and relatively short study duration. Moreover, while comparisons between living environments, as we have done here, should be valid using the same (or similar) instrumentation, it is difficult to quantify the uncertainty of BC and $PM_{2.5}$ measurements in general and no systematic comparisons have so far been conducted among different, common types of BC and $PM_{2.5}$ measurement methodologies in dung-burning smoke. We plan to compare measurements using different approaches in this environment in the future for better uncertainty quantification. We also plan additional measurements of fuel consumption and household ventilation to clarify the relationship between indoor air pollution and living conditions. Additionally, we hope to conduct additional continuous measurements of other air pollutants, such as CO and CO_2, to better understand the combustion condition and combustion process in Tibet. Conducting an epidemiological study on indoor smoke exposure and related health outcomes within the region in households with and without a chimney will enhance our understanding of health impacts due to indoor air pollution. This type of information is so far unavailable for high altitude regions like Tibet,

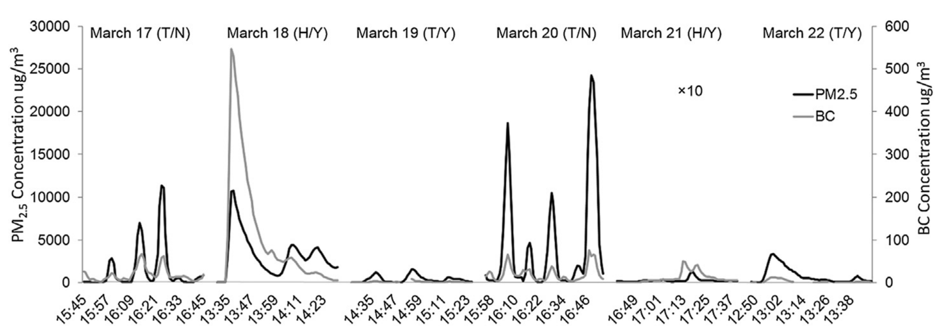

Fig. 5. Peak concentrations of BC and $PM_{2.5}$ observed between 11:40 am and 5:40 pm in six households. T, tent; H, house; Y, with chimney; N, without chimney. Concentrations measured on March 21 are shown as the original value multiplied by 10, due to very low concentration values.

where there are much higher heating needs similar to many other high elevation developing areas using biomass fuels.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.atmosenv.2014.11.060.

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