Atmospheric Environment 45 (2011) 3237–3243

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

Modeling indoor air pollution from cookstove emissions in developing countries using a Monte Carlo single-box model

Michael Johnson [a,*], Nick Lam [a,b], Simone Brant [a], Christen Gray [a], David Pennise [a]

[a] Berkeley Air Monitoring Group, 2124 Kittredge St #57, Berkeley, CA 94704, USA
[b] Environmental Health Sciences, University of California, 725 University Hall, Berkeley, CA 94720, USA

ARTICLE INFO

Article history:
Received 29 December 2010
Received in revised form
18 March 2011
Accepted 21 March 2011

Keywords:
Emission factors
Biomass
Air quality guidelines
Stove testing

ABSTRACT

A simple Monte Carlo single-box model is presented as a first approach toward examining the relationship between emissions of pollutants from fuel/cookstove combinations and the resulting indoor air pollution (IAP) concentrations. The model combines stove emission rates with expected distributions of kitchen volumes and air exchange rates in the developing country context to produce a distribution of IAP concentration estimates. The resulting distribution can be used to predict the likelihood that IAP concentrations will meet air quality guidelines, including those recommended by the World Health Organization (WHO) for fine particulate matter ($PM_{2.5}$) and carbon monoxide (CO). The model can also be used in reverse to estimate the probability that specific emission factors will result in meeting air quality guidelines. The modeled distributions of indoor $PM_{2.5}$ concentration estimated that only 4% of homes using fuelwood in a rocket-style cookstove, even under idealized conditions, would meet the WHO Interim-1 annual $PM_{2.5}$ guideline of 35 μg m^{-3}. According to the model, the $PM_{2.5}$ emissions that would be required for even 50% of homes to meet this guideline (0.055 g MJ-delivered^{-1}) are lower than those for an advanced gasifier fan stove, while emissions levels similar to liquefied petroleum gas (0.018 g MJ-delivered^{-1}) would be required for 90% of homes to meet the guideline. Although the predicted distribution of PM concentrations (median = 1320 μg m^{-3}) from inputs for traditional wood stoves was within the range of reported values for India (108–3522 μg m^{-3}), the model likely overestimates IAP concentrations. Direct comparison with simultaneously measured emissions rates and indoor concentrations of CO indicated the model overestimated IAP concentrations resulting from charcoal and kerosene emissions in Kenyan kitchens by 3 and 8 times respectively, although it underestimated the CO concentrations resulting from wood-burning cookstoves in India by approximately one half. The potential overestimation of IAP concentrations is thought to stem from the model's assumption that all stove emissions enter the room and are completely mixed. Future versions of the model may be improved by incorporating these factors into the model, as well as more comprehensive and representative data on stove emissions performance, daily cooking energy requirements, and kitchen characteristics.

1. Introduction

Emissions from solid fuel cookstoves used in the developing world result in indoor air pollutant concentrations orders of magnitude higher than those typically found in developed world environments. The resulting exposures have been estimated to cause 3–4% of the global burden of disease (Lopez et al., 2006; Smith and Mehta, 2003), with specific health impacts including acute lower respiratory infections, chronic obstructive pulmonary disorder, increased blood pressure, cataracts, low birth weight, tuberculosis, and lung cancer amongst others (Bruce et al., 2000; McCracken et al., 2007; Naeher et al., 2007; Pokhrel et al., 2005; Pope et al., 2010).

The relationships between stove performance metrics (such as emission factors and thermal efficiency) and indoor pollutant concentrations, however, are not well characterized. While many studies have demonstrated that improved stoves can reduce exposures by reducing emissions or venting emissions outdoors (Armendáriz Arnez et al., 2008; Pennise et al., 2009; Saksena et al., 2003), efforts to directly link stove performance metrics to indoor air concentrations are lacking.

Modeling approaches to predict pollutant concentrations based on emission sources and environmental conditions are commonly

* Corresponding author. Tel.: +1 510 649 9355; fax: +1 510 295 2664.
E-mail address: mjohnson@berkeleyair.com (M. Johnson).

1352-2310/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.atmosenv.2011.03.044

used tools in air pollution and climate studies (Bond et al., 2011; Hellweg et al., 2009; Nicas, 2008), yet have not been relied upon as tools for informing on the impact of improved stove projects. Modeling approaches pose several potential benefits, including: 1) estimating potential impacts on indoor air pollution concentrations before conducting expensive and time consuming field studies; 2) evaluating relative importance and impacts of critical stove performance parameters and environmental variables; and 3) providing a means to set stove performance benchmarks or standards which are explicitly linked to air quality guidelines.

There is growing interest in setting standards for stove performance as part of international efforts to promote clean cookstoves. Currently there are globally accepted performance standards for biomass cookstoves, although the Shell Foundation/Aprovecho Benchmarks have been used in laboratory testing for guidance and evaluation of stove design (MacCarty et al., 2010). These benchmarks, however, are not linked to air quality guidelines and are normalized to a standardized water boiling test, which has been shown to be a poor predictor of emissions from normal stove use in homes (Johnson et al., 2008, 2009; Roden et al., 2009).

This paper presents a first approach toward addressing these needs with a simple Monte Carlo single-box model, which predicts indoor concentrations given a stove's emission performance and usage, as well as kitchen characteristics. Here we illustrate the utility of the model by presenting simulated distributions of IAP concentrations in kitchens based on a series of stove/fuel scenarios, comparing them with the World Health Organization (WHO) Air Quality Guidelines (AQGs) for $PM_{2.5}$ and CO. Finally, the model is used to predict the stove performance characteristics that would be required for a given percentage of homes to meet the WHO AQGs.

2. Methods

2.1. Monte Carlo single-box model

The single-box model employed here predicts room concentrations based on stove emissions and kitchen characteristics. Indoor air pollutant concentrations were modeled assuming a well mixed room with single constant emission source. The model assumes instantaneous mixing with zero backflow to the room, that removal of the pollutant from the air is dominated by ventilation, and competing loss mechanisms are negligible (e.g. surface reactions, particle settling). The model is described mathematically as:

$$C_t = \frac{Gf}{\alpha V}\left(1 - e^{-\alpha t}\right) + C_o\left(e^{-\alpha t}\right), \tag{1}$$

where, C_t = Concentration of pollutant at time t (mg m^{-3}); G = emission rate (mg min^{-1}); α = first order loss rate (nominal air exchange rate) (min^{-1}); V = kitchen volume (m^3); t = time (min); C_0 = concentration from preceding time unit (mg m^{-3}); f = fraction of emissions that enters the kitchen environment.

The emission rate and cooking duration are functions of the power, thermal efficiency, and emission factors for a given fuel/stove combination, as well as the amount of required energy-delivered for cooking. Emission rate G was calculated as:

$$G = \frac{E_F}{E_D} P, \tag{2}$$

where E_F is the fuel based emission factor (mg pollutant kg fuel^{-1}), E_D is the energy density of the fuel (MJ kg^{-1})[1], and P is the stove power (MJ min^{-1}). Emission rates were constant during each cooking event for each respective model iteration. Daily cooking energy required was split into three equal events, with the duration (T_C) of each determined as:

$$T_C = \frac{E_{DC}/3}{P(\eta)}, \tag{3}$$

where E_{DC} is total daily cooking energy required (MJ) and η is stove's thermal efficiency (%).

A Monte Carlo approach was used to incorporate the variability in model parameters, resulting in a predicted distribution of $PM_{2.5}$ and CO concentrations. 5000 simulations of a day of cooking were run, with the inputs randomly selected from their respective probability distribution.

2.2. Model inputs

For the purposes of illustrating the model, we present results based on inputs selected to represent scenarios specific to the Indian context, although the model can be applied to any region where sufficient data is available. India was selected as the available data for inputs was relatively comprehensive, and it represents a country with a large number of homes using solid fuel stoves. Four different scenarios were run to illustrate the utility of the model: 1) wood-burning traditional chulha with inputs based on controlled cooking tests[2] conducted in Indian homes by regular stove users; 2) wood-burning Envirofit G3300 rocket stove with inputs based on controlled cooking tests conducted in Indian homes by regular stove users; 3) the same Envirofit G3300 stove with inputs based on water boiling tests[3] conducted in the laboratory; and 4) an LPG stove with inputs based on water boiling tests conducted in the laboratory. Table 1 provides a summary of the model parameters and their basis for use in the model.

Air exchange rate distributions were based on three studies conducted in India, which were estimated from the decay rate of carbon monoxide after the conclusion of a cooking event (McCracken and Smith, 1998). Distributions of kitchen volumes were also estimated based on measurements in Indian homes. Daily cooking energy for India was obtained from an analysis by Habib et al. (2004), who combined national survey data for food consumption with the specific energy required for cooking common foods. Emission factors, thermal efficiency, and stove power were drawn from four sources: Inputs for in-home use of traditional chulhas and the G3300 were from a study by Berkeley Air Monitoring Group and Sri Ramachandra University in Tamil Nadu, which was conducted using a series of controlled cooking tests in 10 rural homes. The lab-based inputs for the G3300 were from water boiling tests conducted at the Engines and Energy Conversion Lab at Colorado State University. The inputs for LPG emission factors, thermal efficiency, and power were from Smith et al. (2000), with an additional PM emission factor for LPG from Habib et al. (2008) included in the mean.

All distributions were assumed to be lognormal, which is common for environmental data. Distributions were truncated at limits deemed highly improbable for the given parameter, while still allowing relatively extreme, yet possible data points (e.g. very small or large kitchens). All truncated distributions contained over 90% of the data of the entire distribution. The fraction of emissions

[1] 18 MJ kg^{-1} for dry wood and 46 MJ kg^{-1} for LPG (Smith et al., 2000).

[2] The controlled cooking test is a stove performance test where a typical, local meal is prepared by local cooks on multiple stoves in order to compare stove performance metrics to complete a typical cooking task.

[3] The water boiling test is a standardized laboratory test where water is brought to a boil and then simmered for 45 min, from which various stove performance metrics can be derived.

Table 1
Model inputs.

Parameter	Unit	Mean	Min	Max	COV	Basis
Air exchange rate (α)	hr^{-1}	25	3	60	0.6	(ARC, 2006; Bhangar, 2006; Brant et al., 2010)
Kitchen volume (V)	m^3	30	3	100	0.5	(Bhangar, 2006; Brant et al., 2010; Brant et al., 2009; Saksena et al., 2003)
Fraction of emissions entering room (f)	Unitless	1	–	–	–	Only non-chimney stoves are presented here
Cooking energy required	MJ-delivered	11	3	30	0.5[a]	(Habib et al., 2004)
Stove Power						
Traditional Chulha	KJ s^{-1}	4.9	2	15	0.7	(Brant et al., 2010)
G3300 In-home CCT	KJ s^{-1}	3.8	2	10	0.3	(Brant et al., 2010)
G3300 Lab WBT	KJ s^{-1}	3.1	2	10	0.1	(EECL, 2009)
LPG	KJ s^{-1}	1.6	0.5	5	0.1	(Smith et al., 2000)
Thermal Efficiency						
Traditional Chulha	%	14	5	35	0.1	(Brant et al., 2010)
G3300 In-home CCT	%	22	10	45	0.3	(Brant et al., 2010)
G3300 Lab WBT	%	29	20	45	0.1	(EECL, 2009)
LPG	%	54	40	60	0.1	(Smith et al., 2000)
Emission factors						
Traditional Chulha	$PM_{2.5}$ (g kg^{-1})[b]	5.2	1	10	0.2	(Brant et al., 2010)
	CO (g kg^{-1})	64	10	100	0.2	(Brant et al., 2010)
G3300 In-home CCT	$PM_{2.5}$ (g kg^{-1})	5.0	0.2	10	0.2	(Brant et al., 2010)
	CO (g kg^{-1})	47	10	90	0.2	(Brant et al., 2010)
G3300 Lab WBT	$PM_{2.5}$ (g kg^{-1})	1.6	0.5	5	0.5	(EECL, 2009)
	CO (g kg^{-1})	34	5	80	0.3	(EECL, 2009)
LPG	$PM_{2.5}$ (g kg^{-1})	0.36	0.05	1	0.4	(Habib et al., 2008; Smith et al., 2000)
	CO (g kg^{-1})	15	2	40	0.2	(Smith et al., 2000)

[a] Notes: The coefficient of variation on a home-by-home basis was not available for this distribution. 0.5 is used a reasonable estimate for this parameter.
[b] PM emission factors from these studies were measured as total suspended particulates. Size distributions for combustion particles are generally small with almost all mass from particles less than 2.5 μm in diameter, so we report these as $PM_{2.5}$ for simple comparison with AQGs.

entering the room (f) was conservatively set at one, given that modeled scenarios were for non-chimney stoves. The initial kitchen concentration (C_0) was set to zero so that the model concentrations accounted for only those stemming from stove emissions, although the model easily accommodates discrete or distributions of background concentrations.

3. Results

3.1. Model output

Fig. 1 shows an example of minute-by-minute kitchen concentrations for 20 simulations of a single cooking event with the G3300 stove. Each simulation is characterized by a rapid increase in $PM_{2.5}$ concentrations at the onset of cooking, reaching a steady state when the loss rate equals that of the emissions contribution, then decaying after the cooking event is over. The variability in simulations is a result of random selection of values from the given distributions for the input parameters. Differences in cooking event times are the product of variability in cooking energy required, stove power, and thermal efficiency, while the maximum $PM_{2.5}$ concentration is a function of these parameters as well as the magnitude of the emission factors, ventilation, and kitchen volume. The full model for a given fuel/stove scenario includes three cooking events over 24 h with 5000 simulated runs, which is what was used to tabulate the summary statistics and output distributions described below.

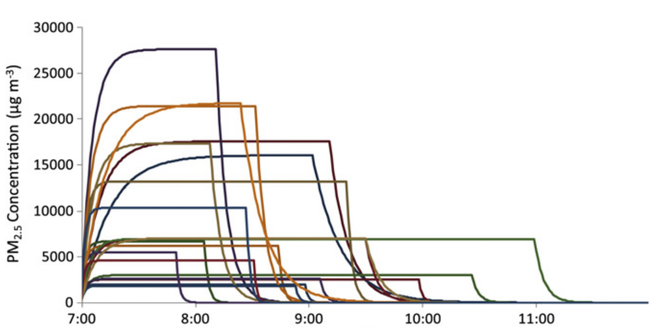

Fig. 1. Example output of the G3300 for a single cooking event.

Table 2 presents summary statistics and the percentage of simulations which met respective WHO AQGs for each fuel/stove input scenario. The modeled distributions of $PM_{2.5}$ and CO kitchen concentrations were highest for the traditional chulha, followed by the G3300 with in-home and laboratory inputs, respectively, with LPG resulting in the lowest concentrations. This is also illustrated in Fig. 2, which shows the modeled distributions of $PM_{2.5}$ and CO kitchen concentrations, with selected AQG markers provided for reference. All distributions are positively skewed as a result of the lognormal input distributions. This skewness also resulted in the means exceeding the respective medians for each distribution (see Table 2). The differences in the distributions of kitchen concentrations correspond with the inputs, as the traditional chulha had the lowest thermal efficiency and highest emission factors, while the other scenarios were sequentially higher in thermal efficiency and lower in emission factors of $PM_{2.5}$ and CO.

This trend also is reflected in the percentage of simulations which resulted in output concentrations meeting the WHO AQGs. Only the G3300 (laboratory-based inputs) and LPG produced distributions with simulations which met any of the $PM_{2.5}$ guidelines, although even LPG resulted in only ~50% of simulations meeting the strictest final guideline of 10 μg m^{-3}. Higher percentages of modeled kitchen CO concentrations fell within WHO standards for all stoves. All simulations of LPG usage met the CO AQGs, and even the traditional chulha's inputs resulted in ~17% of simulations meeting the 24-h CO AQG of 7 mg m^{-3}.

Table 2
Summary statistics of model output and percent of simulations meeting WHO Air Quality Guidelines for four different stove scenarios.

	Traditional chulha (wood)	G3300 field inputs (wood)	G3300 WBT inputs (wood)	LPG
Particulate matter model output				
Mean ($\mu g\ m^{-3}$)	1975	1266	328	15
Median ($\mu g\ m^{-3}$)	1320	831	197	10
10th percentile ($\mu g\ m^{-3}$)	429	258	55	3
90th percentile ($\mu g\ m^{-3}$)	4107	2718	717	33
Percent of simulations meeting WHO $PM_{2.5}$ guidelines				
24-h Int 1 (75 $\mu g\ m^{-3}$)	0%	0%	17%	98%
24-h Final (25 $\mu g\ m^{-3}$)	0%	0%	2%	84%
Annual Int 1 (35 $\mu g\ m^{-3}$)	0%	0%	4%	91%
Annual Final (10 $\mu g\ m^{-3}$)	0%	0%	0%	52%
Carbon monoxide model output				
Mean ($mg\ m^{-3}$)	25	12	7	1
Median ($mg\ m^{-3}$)	16	8	4	0
10th percentile (mg^{-3})	5	2	1	0
90th percentile (mg^{-3})	51	26	14	1
Percent of simulations meeting WHO carbon monoxide guidelines				
24 h (7 $mg\ m^{-3}$)	17%	46%	69%	100%
8 h (10 $mg\ m^{-3}$)	9%	33%	56%	100%
60 min (30 $mg\ m^{-3}$)	12%	33%	56%	100%
30 min (60 $mg\ m^{-3}$)	31%	58%	80%	100%
15 min (100 $mg\ m^{-3}$)	53%	80%	93%	100%

Notes: AQGs are from (WHO, 2006, 2010).

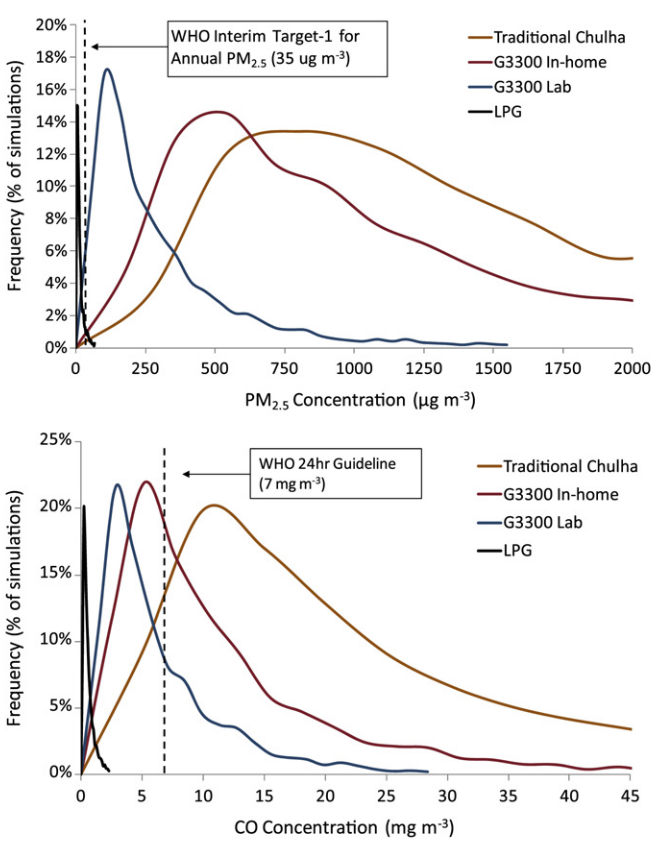

Fig. 2. Model output distributions of $PM_{2.5}$ (top) and CO concentrations.

4. Discussion

4.1. Model performance

4.1.1. Accuracy

The model appears to perform well when compared with published kitchen concentrations of PM and CO for traditional stove users in India. The mean modeled 24-h concentration for $PM_{2.5}$ was 1975 $\mu g\ m^{-3}$, and published 24-h PM[4] concentrations from 11 studies ranged from 108 to 3522 $\mu g\ m^{-3}$ with a mean of 1313 $\mu g\ m^{-3}$ (Saksena et al., 2003; Smith et al., 2007). Similarly for CO, the mean of the modeled distribution assuming chulha inputs was 25 mg m^{-3}, which fell within the range of 4–59 mg m^{-3} for published India-specific data and was slightly higher than the 18 mg m^{-3} mean from these studies (Saksena et al., 2003; Smith et al., 2007).

In general, we suspect the model overestimates kitchen concentrations relative to the assumed magnitude of stove emissions. In addition to the higher modeled mean concentrations compared to published data cited above, we analyzed two sets of data for which emission rates and indoor air pollution concentrations of CO were simultaneously monitored. In a set of eight kitchens in Kenya, we found the model to overestimate measured CO concentrations by 8 fold for charcoal stoves and 3 fold for kerosene stoves. For the same in-field study which provided the stove performance inputs based on cooking in Indian homes, however, we found that the model underestimated measured CO concentrations by approximately one half[5]. The source for these discrepancies may arise from several factors, although perhaps the most likely cause is the assumption that all emissions enter the room and are completely mixed, which we discuss more thoroughly in the following sections.

4.1.2. Sensitivity

The factors which contributed to most of the variance in kitchen concentrations between simulations were exchange rate, kitchen volume, and cooking energy, ranging from 34 to 42%, 23–28%, and 20–25%, respectively. Emission factors and thermal efficiency contributed 4–22% and 1–9% of the variance in $PM_{2.5}$ simulations and 4–9% and 1–8% for CO simulations, respectively. While these relative contributions to output variance suggest that kitchen volume and ventilation have a large impact on kitchen concentrations and are therefore of great importance for model accuracy, they should be considered relatively constant within each respective home for which a stove intervention would take place. So although they are responsible for much of the variability in IAP concentrations, the stove performance factors are the most critical ones for assessing potential impacts.

4.2. Assumptions and limitations

4.2.1. Inputs

There are several areas where the model could be improved with more comprehensive data and/or refinement of the assumptions. As with any model, the quality of the output is limited by the quality of the inputs. There is very little published data available for daily cooking energy needs in developing regions, and here we were reliant on a single source for India (Habib et al., 2004). Clearly a wider range of sources would provide a more solid basis for required cooking energy. Kitchen volumes and ventilation rates

[4] These studies included $PM_{2.5}$, $PM_{4.0}$, and total suspended particulates.

[5] A more detailed description of these findings as well as results for individual test events from India and Kenya can be found in the Supplementary Data section.

were drawn from multiple sources (ARC, 2006; Bhangar, 2006; Brant et al., 2010, 2009; Saksena et al., 2003) covering a range of Indian homes. Here, we are reasonably confident in our estimates, although these parameters will vary considerably depending on housing type and weather conditions, and therefore application of the model for a specific location will require region-specific inputs.

We are also confident in the quality of the inputs related to stove performance: thermal efficiency, emission factors, and power. The critical consideration for these inputs, however, is not the quality of the data, but rather how representative the inputs are of normal stove use. We presented the output from the G3300 based on both laboratory and field conditions to highlight the difficulties in predicting real stove performance using controlled laboratory testing (see Fig. 2). The idealized fuel and fire-tending conditions of laboratory testing likely led to higher thermal efficiency and lower PM and CO emission factors for the G3300 compared to those from the controlled cooking tests in homes. Even the controlled cooking tests may overestimate stove performance as the fire is constantly tended and the fuel is relatively uniform. Thus, a major challenge moving forward will be to determine how to fairly interpret modeled kitchen concentration estimates should they be based on laboratory testing, given that the value of the model is undermined if extensive field testing is required. Other testing approaches, which attempt to account for a broader range of stove use conditions have been proposed (Johnson et al., 2009; Prasad et al., 1985) and may provide better inputs for modeling approaches.

4.2.2. Emission sources

For the sake of simplicity, the model assumes that the source of all IAP is from a single stove source with a constant emission rate, and that all emissions from that source enter the room. In reality, there are generally several sources of indoor air pollution, and in many homes multiple stoves are used for various tasks, some of which do not involve cooking (e.g. boiling bath water). Contributions from outdoor air pollution were not included, although these clearly do impact indoor air pollution concentrations and can be input into the model as a discrete or a distribution of values. Contributions from outdoor sources generally make small relative impacts on IAP concentrations for traditional stove users, but could be a larger relative source of IAP for homes with cleaner cooking technologies.

While we assumed here that all emissions from the assumed single stove enter and are mixed throughout the room ($f = 1$ in Eq. (1)), in many kitchens stoves are placed under ventilation windows or other openings which immediately vent considerable fractions of emissions outdoors before they are mixed throughout the room. The fraction of emissions that ultimately becomes mixed in the kitchen is an especially difficult parameter to measure in homes, and thus, we opted to conservatively assume that all emissions vent indoors and are mixed in the room. Running the model including an input distribution for the fraction of emissions entering the room with a mean of 0.5 (half the emissions enter the room) and COV of 0.5, for example, resulted in mean CO concentrations ~40% less than when all emissions were assumed to enter the room.

Assuming a constant emission rate is also unrealistic – especially for solid fuel stoves, although the model can be adapted to allow input of minute-by-minute emission profiles. Minute-by-minute emission profiles would likely provide more accurate pollutant concentration results over shorter time periods (e.g. 15 min and 30 min). When examining 24-h, 8-h and 1-h average concentrations, however, a constant emission rate is a reasonable assumption.

4.2.3. Stratification of IAP concentrations

To keep the model simple as a first approach, we have assumed that the emissions instantly and completely mix throughout the room. In real kitchens, the IAP concentrations can be highly stratified, especially vertically, due to the emission plume's upward convection. For example, an IAP study in India found that total suspended particulate concentrations in the kitchen at 1.5 m were approximately double those measured at 0.5 m (Kandpal et al., 1995). We also investigated the level of stratification in five rural India kitchens during 70 cooking events, for which GasBadge Pro CO monitors (Industrial Scientific, Oakdale, USA) were spaced 0.5–1.0 m apart across four vertical and four horizontal positions (eight monitors in total). Fig. 3 shows an example of the vertical stratification during a cooking event, for which CO concentrations sequentially increased with height. The median CO ratio of the highest to lowest positioned monitor was 16 for all cooking events ($n = 70$), indicating the difficulties using a single concentration to represent the kitchen.

Standard protocols developed for measuring IAP for household energy projects call for kitchen concentrations to be measured one horizontal meter from the center of stove and at a height of 1.5 m (Rouse, 2008), which is supposed to represent an approximate exposure height for someone standing near the stove. To evaluate how representative IAP concentrations measured at a height of 1.5 m are of the kitchen's average IAP concentration (which represents the model's theoretical output), we calculated the weighted average or integrated kitchen concentration from the eight CO monitors, weighting each by the relative volume of kitchen air represented by that monitor. The median ratio for the 70 cooking events of the integrated kitchen concentration to the 1.5 m concentration was 0.95 which suggests for this study that the 1.5 m location was representative of overall CO concentration in the kitchen. Thus the model's theoretical output, which is an integrated concentration, as it assumes complete mixing throughout the kitchen volume, would appear to be a reasonable proxy for the standardized 1.5 m height in these specific kitchens.

Kitchen concentrations, however, are clearly not well mixed, which suggests the model can produce estimates with substantial error. The model's overestimation of CO concentrations measured at 1.5 m high in Kenyan kitchens (eight fold for charcoal and three fold for kerosene), for example, could very well arise from the model not accounting for stratification. While we can only speculate, the eight fold over prediction for charcoal and three fold for kerosene is suggestive that stratification is a primary cause for error, as the charcoal stove's plume likely has greater upward convection whereas the kerosene stove's plume may be more likely to be mixed.

Other models (e.g. multi-box model, eddy diffusion model, and single-box with mixing factors) may ultimately provide better

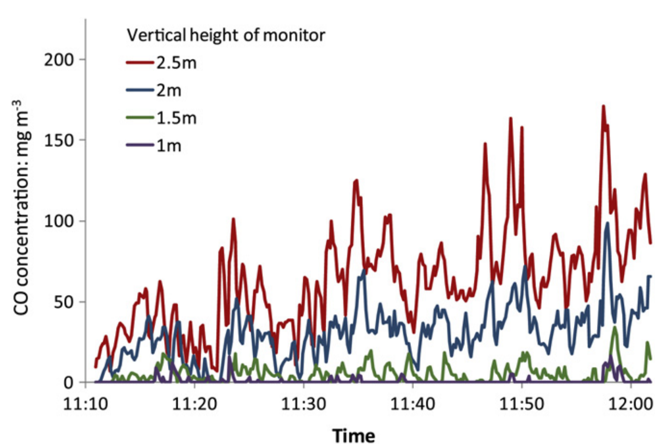

Fig. 3. Minute-by-minute concentrations of CO, showing the stratification across four vertical heights in an Indian kitchen during a cooking event.

estimates (Keil and Nicas, 2003; Nicas, 2000; Sahmel et al., 2009). As a first approach, however, we chose a single-box model because of its transparency and relative simplicity (Hellweg et al., 2009). This allowed for the investigation of different stove and kitchen scenarios while minimizing the need to utilize unjustified assumptions and parameters required in more complex models.

4.3. Emission limits to meet AQGs

The model can also be used to estimate the emission factors (or emission limits) necessary to meet a given AQG. Here we demonstrate this utility by estimating emission factors that would result in 50%, 75%, and 90% of Indian homes meeting WHO Guidelines for $PM_{2.5}$ and CO. The emission limit is reported as $PM_{2.5}$ or CO MJ-delivered^{-1}, as this metric combines a stove's thermal efficiency with the fuel based emission factor to provide a single number better suited for use as a benchmark. The annual $PM_{2.5}$ guideline was selected as a reference point since exposure to biomass smoke is a chronic experience for stove users, and the interim 1 level (35 μg m^{-3}) was selected as a more realistic goal than the final AQG (10 μg m^{-3}), which is already exceeded by ambient concentrations in many environments of developed regions. The 24-h CO AQG was considered here, as the WHO currently does not have a recommended annual CO AQG.

Table 3 shows the $PM_{2.5}$ and CO emission factors for which the model predicted 50, 75, and 90% of homes would meet the AQGs. Even the least conservative estimated PM emission factor benchmark (0.055 g MJ-delivered^{-1}), for which only half of the homes meet the WHO AQG, is ~6 times lower than that of the G3300 under idealized laboratory conditions (0.31 g MJ-delivered^{-1}), and even slightly lower than the emission factor reported for an advanced, wood-burning gasifier fan stove tested in the laboratory (0.07 g MJ-delivered^{-1}) (MacCarty et al., 2008). Having 90% of homes meet the guideline, according to the model, would require an emission factor (0.018 g MJ-delivered^{-1}) nearing that of LPG (0.007–0.019 g MJ-delivered^{-1}) (Habib et al., 2008; Smith et al., 2000).

The G3300's CO emission factor assuming laboratory conditions (6.5 g MJ-delivered^{-1}) was less than the emission factor predicted for 50% of homes to meet WHO 24 h CO AQGs (10.9 g MJ-delivered^{-1}). The G3300's emission factor, however, was still approximately double that of the emission factor predicted for 90% of homes to meet the CO AQG (3.6 g MJ-delivered^{-1}).

Even allowing for considerable model error, these emission factors suggest that benchmarks based on WHO AQGs, especially for $PM_{2.5}$, present a high bar for biomass stoves. The matter of appropriate standardized testing, which would in some form be required for evaluating stoves against the benchmarks, would also have to be addressed. Fig. 2 demonstrates, as does prior research (Bailis et al., 2007; Johnson et al., 2009; Roden et al., 2009), that differences in stove performance between the laboratory and in homes are substantial. These differences will need to be reconciled through new testing and/or modeling approaches should attainment of a given performance benchmark by a stove be expected to translate into similar field performance.

Table 3
Emission factors (g MJ-delivered^{-1}) required to meet selected WHO AQGs.

	% Meeting WHO AQG		
	50%	75%	90%
WHO Annual Int. 1 $PM_{2.5}$ Guideline (35 μg m^{-3})			
g MJ-delivered^{-1}	0.055	0.030	0.018
Mean Concentration (μg m^{-3})	52	28	17
Median Concentration (μg m^{-3})	35	19	11
WHO 24 hr CO Guideline (7 mg m^{-3})			
g MJ-delivered^{-1}	10.9	6.0	3.6
Mean Concentration (mg m^{-3})	10	6	3
Median Concentration (mg m^{-3})	7	4	2

5. Model improvements

The simple Monte Carlo single-box model presented here can be used to predict kitchen concentrations of air pollutants given emission performance data for various stove/fuel combinations and information about typical cooking needs and kitchen characteristics. This capacity can be a useful approach for preliminary, cost-effective evaluation of a stove's potential IAP impacts, as well as linking health-based air quality guidelines to stove performance standards. Moving forward, however, there are improvements that could be made to increase model performance:

- Better accounting of pollutant mixing would help address the stratification of IAP concentrations in kitchens. Incorporation of a mixing factor into the model, preferably derived through more field evaluations, would be an important refinement to increase the accuracy of the model.
- The quality of the model could be improved with more comprehensive input data. Data on daily cooking energy required, as well as kitchen volumes and ventilation rates are relatively scarce and, to our knowledge, there have been no efforts to characterize the fraction of emissions that vent outdoors before being mixed throughout the kitchen.
- More studies reporting emission factors during normal daily stove use from various stove/fuel combinations being used around the world would provide a baseline and valuable context for model results. Ideally these studies could be combined with real-world kitchen concentration data to inform on emissions-IAP concentration relationships and help validate the model.
- Current standardized tests are poor indicators of stove performance in homes. Understanding and reconciling the differences between stove performance in the laboratory and field will be a necessary step for accurately modeling IAP concentrations based on laboratory testing.

Acknowledgments

We would like to thank Kirk R. Smith, Rufus Edwards, and Dana Charron for their input and guidance on this project, as well as Mark Nicas and Tom McKone for early discussions on household indoor air quality models. We are especially grateful to the participants who welcomed us into their homes in Kenya and India. Funding for this project was provided in part by the Shell Foundation.

Appendix. Supplementary data

Supplementary data associated with the article can be found in online version, at doi:10.1016/j.atmosenv.2011.03.044.

References

ARC, 2006. Perfomance Benchmarks for Improved Stoves: A Proposal for Adoption. Aprovecho Research Center, Cresswell.

Armendáriz Arnez, C., Edwards, R., Johnson, M., Zuk, M., Serrano, P., Rojas Bracho, L., Riojas-Rodríguez, H., Masera, M., 2008. Reduction in particulate and carbon monoxide levels associated with the introduction of a patsari improved cook stove in rural Mexico. Indoor Air 18, 93–105.

Bailis, R., Berrueta, V., Chengappa, C., Dutta, K., Edwards, R., Masera, O., Still, D., Smith, K.R., 2007. Performance testing for monitoring improved biomass stove

interventions: experiences of the household energy and health project. Energy for Sustainable Development 11, 57–70.
Bhangar, S., 2006. Indoor Air Quality of Households with Improved and Traditional Stoves in Kaldari, India. Health, Environment and Development. University of California, Berkeley.
Bond, T.C., Zarzycki, C., Flanner, M.G., Koch, D.M., 2011. Quantifying immediate radiative forcing by black carbon and organic matter with the specific forcing pulse. Atmos. Chem. Phys. Discuss. 10, 15713–15753.
Brant, S., Johnson, M., Pennise, D., Charron, D., 2010. Controlled Cooking Test Evaluation of the B1200 and G3300 Cookstoves in Tamil Nadu, South India. Berkeley Air Monitoring Group and Sri Ramachandra University, Department of Environmental Health Engineering.
Brant, S., Pennise, D., Charron, D., 2009. Monitoring and Evaluation of the B1100 and S2100 Cookstoves in South India. Berkeley Air Monitoring Group and Sri Ramachandra University, Department of Environmental Health Engineering.
Bruce, N., Perez-Padilla, R., Albalak, R., 2000. Indoor air pollution in developing countries: a major environmental and public health challenge. B. World Health Organ 78, 1078–1092.
EECL, 2009. Emissions and Performance Report: G3300 Engines and Energy Conversion Lab, Department of Mechanical Engineering at Colorado State University, Fort Collins.
Habib, G., Venkataraman, C., Bond, T.C., Schauer, J.J., 2008. Chemical, microphysical and optical properties of primary particles from the combustion of biomass fuels. Environ. Sci. Technol. 42, 8829–8834.
Habib, G., Venkataraman, C., Shrivastava, M., Banerjee, R., Stehr, J.W., Dickerson, R.R., 2004. New methodology for estimating biofuel consumption for cooking: atmospheric emissions of black carbon and sulfur dioxide from India. Glob. Biogeochem. Cycles 18.
Hellweg, S., Demou, E., Bruzzi, R., Meijer, A., Rosenbaum, R.K., Huijbregts, M.A.J., McKone, T.E., 2009. Integrating human indoor air pollutant exposure within life cycle impact assessment. Environ. Sci. Technol. 43, 1670–1679.
Johnson, M., Edwards, R., Alatorre Frenk, C., Masera, O., 2008. In-field greenhouse gas emissions from cookstoves in rural Mexican households. Atmos. Environ. 42, 1206–1222.
Johnson, M., Edwards, R., Berrueta, V., Masera, O., 2009. New approaches to performance testing of improved cookstoves. Environ. Sci. Technol. 44, 368–374.
Kandpal, J.B., Maheshwari, R.C., Kandpal, T.C., 1995. Indoor air pollution from domestic cookstoves using coal, kerosene and LPG. Energ. Convers. Manag. 36, 1067–1072.
Keil, C.B., Nicas, M., 2003. Predicting room vapor concentrations due to spills of organic solvents. Aiha J. 64, 445–454.
Lopez, A.D., Mathers, C.D., Ezzati, M., Jamison, D.T., Murray, C.J.L., 2006. Global and regional burden of disease and risk factors, 2001: systematic analysis of population health data. Lancet 367, 1747–1757.
MacCarty, N., Ogle, D., Still, D., Bond, T., Roden, C., 2008. A laboratory comparison of the global warming impact of five major types of biomass cooking stoves. Energy for Sustainable Development 12, 56–65.
MacCarty, N., Still, D., Ogle, D., 2010. Fuel use and emissions performance of fifty cooking stoves in the laboratory and related benchmarks of performance. Energy for Sustainable Development 14, 161–171.
McCracken, J.P., Díaz, A., K.R., S., Mittleman, M., Schwartz, J., 2007. Chimney stove intervention to reduce long-term air pollution exposure lowers blood pressure among Guatemalan women. Environ. Health Perspect. 115, 996–1001.
McCracken, J.P., Smith, K.R., 1998. Emissions and efficiency of improved woodburning cookstoves in highland Guatemala. Environ. Int. 24, 739–747.
Naeher, L.P., Brauer, M., Lipsett, M., Zelikoff, J.T., Simpson, C.D., Koenig, J.Q., Smith, K.R., 2007. Woodsmoke health effects: a review. Inhal. Toxicol. 19, 67–106.
Nicas, M., 2000. Two-zone models. In: Keil, C.B. (Ed.), Mathematical Models for Estimating Occupational Exposure to Chemicals, first ed. AIHA Press, Fairfax, VA, p. 106.
Nicas, M., 2008. Quantitative surveying- application of mathematical modeling to estimate air contaminant exposure. In: Perkins, J.L. (Ed.), Modern Industrial Hygiene, second ed. ACGIH, Cincinnati.
Pennise, D., Brant, S., Agbeve, S.M., Quaye, W., Mengesha, F., Tadele, W., Wofchuck, T., 2009. Indoor air quality impacts of an improved wood stove in Ghana and an ethanol stove in Ethiopia. Energy for Sustainable Development 13, 71–76.
Pokhrel, A.K., Smith, K.R., Khalakdina, A., Deuja, A., Bates, M.N., 2005. Case-control study of indoor cooking smoke exposure and cataract in Nepal and India. Int. J. Epidemiol. 34, 702–708.
Pope, D.P., Mishra, V., Thompson, L., Siddiqui, A.R., Rehfuess, E.A., Weber, M., Bruce, N.G., 2010. Risk of low birth weight and stillbirth associated with indoor air pollution from solid fuel use in developing countries. Epidemiologic Reviews 32, 70–81.
Prasad, K.K., Sangen, E., Visser, P., 1985. Woodburning cookstoves. In: Hartnett, J.P., Thomas, F., Irvine, J. (Eds.), Advances in Heat Transfer. Elsevier, pp. 159–317.
Roden, C.A., Bond, T.C., Conway, S., Osorto Pinel, A.B., MacCarty, N., Still, D., 2009. Laboratory and field investigations of particulate and carbon monoxide emissions from traditional and improved cookstoves. Atmos. Environ. 43, 1170–1181.
Rouse, J., 2008. Evaluating Household Energy and Health Interventions: A Catalogue of Methods. World Health Organization.
Sahmel, J., Unice, K., Scott, P., Cowan, D., Paustenbach, D., 2009. The use of multizone models to estimate an airborne chemical contaminant generation and decay profile: occupational exposures of hairdressers to vinyl chloride in hairspray during the 1960s and 1970s. Risk Anal. 29, 1699–1725.
Saksena, S., Thompson, L., Smith, K., 2003. The Indoor Air Pollution and Exposure Database: Household Pollution Levels in Developing Countries. http://ehs.sph.berkeley.edu/heh/hem/documents/iapi.pdf.
Smith, K.R., Dutta, K., Chengappa, C., Gusain, P.P.S., Berrueta, O.M.A.V., Edwards, R., Bailis, R., Shields, K.N., 2007. Monitoring and evaluation of improved biomass cookstove programs for indoor air quality and stove performance: conclusions from the household energy and health project. Energy for Sustainable Development 11, 5–18.
Smith, K.R., Mehta, S., 2003. The burden of disease from indoor air pollution in developing countries: comparison of estimates. Int. J. Hyg. Environ. Health 206, 279–289.
Smith, K.R., Uma, R., Kishore, V.V.N., Lata, K., Joshi, V., Zhang, J., Rasmussen, R.A., Khalil, M.A.K., 2000. Greenhouse Gases from Small-scale Combustion Devices in Developing Countries. United States Environmental Protection Agency, Washington D.C.
WHO, 2006. WHO guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide. World Health Organization Press, Geneva.
WHO, 2010. WHO guidelines for indoor air quality: selected pollutants. World Health Organization Regional Office for Europe, Bonn.