Modeling Indoor Air Pollution Concentrations from Stove Emissions Using a Monte Carlo Single-Box Model

Michael Johnson[1], David Pennise[1], Nicholas Lam[1, 2], Simone Brant[1], Dana Charron[1] , Christen Gray[1], Kirk R. Smith[2]
1. Berkeley Air Monitoring Group
2. University of California, Berkeley

ETHOS

BERKELEY AIR MONITORING GROUP

SHELL FOUNDATION

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Purpose of Model

- Assist program/stove development:
  - Examine the relationship between emissions from stove/fuel combinations and the resulting indoor air pollution concentrations.
  - Estimate CO and $PM_{2.5}$ kitchen concentrations, given the emissions of a stove/fuel and some understanding of typical usage patterns and kitchen volume and ventilation.

- Link standards with air quality guidelines:
  - Estimate the likelihood that WHO Guidelines will be met given a specific emissions factor (g per MJ-delivered).
  - Determine the emissions factors required to meet the WHO Guidelines with a certain degree of confidence (using the model in reverse).

Description of Model (1)

$$C_t = \frac{qf}{\propto V}(1 - e^{-\propto t}) + C_o\,(e^{-\propto t})$$

C_t = Concentration of pollutant ($PM_{2.5}$ or CO) at time t (mg/m^3)

q = emission rate (mg/min)

α = nominal air exchange rate (ventilation rate) (min^{-1})

V = kitchen volume (m^3)

t = time (min)

C_o = concentration from preceding time unit (mg/m^3)

f = fraction of emissions that enters the kitchen

Note: time and emissions rates are a function of thermal efficiency, emission factor, power, and daily cooking energy needs

Description of Model (2)

- Monte Carlo modeling – compute model results by performing many of iterations of the model (typically 500-10,000).
- Uses repeated random sampling of typical parameter values within a given distribution
  - Allows input of typical ranges (distributions) of model parameters: room volume, ventilation rate, emission factors, thermal efficiency, stove power, and required cooking energy
- Monte Carlo method allows us to include the variability in stove efficiency and kitchen conditions, which yields probabilistic results – more indicative of the variability seen during normal daily stove use.

Description of Model (3)

- A minute by minute kitchen concentration profile is created for the observation period (24 hours) for each iteration of the model
- A variety of useful statistics can be generated
  - 15-min max, 30-min max, 1-hr max, 8-hr max, and 24-hour average concentrations
- Resulting distribution of modeled concentrations provides estimate of probability of meeting or exceeding a particular air quality guideline (or other user-defined target).

Illustration of model

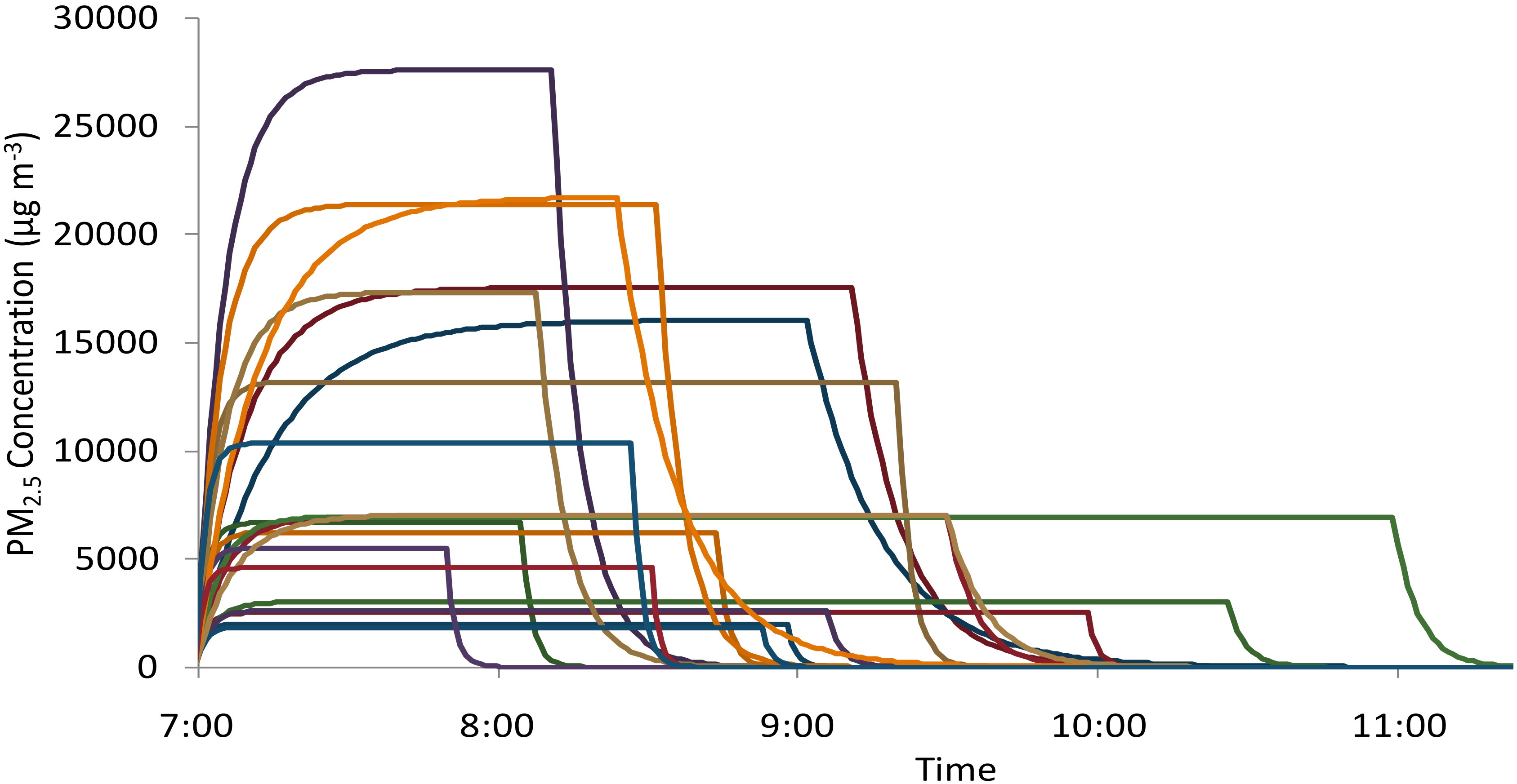
- Estimated distribution of $PM_{2.5}$ and CO for four scenarios in the India context:
  - LPG, G3300 WBT in lab, G3300 CCT in homes, chulha CCT in homes.

Summary of Model Parameters

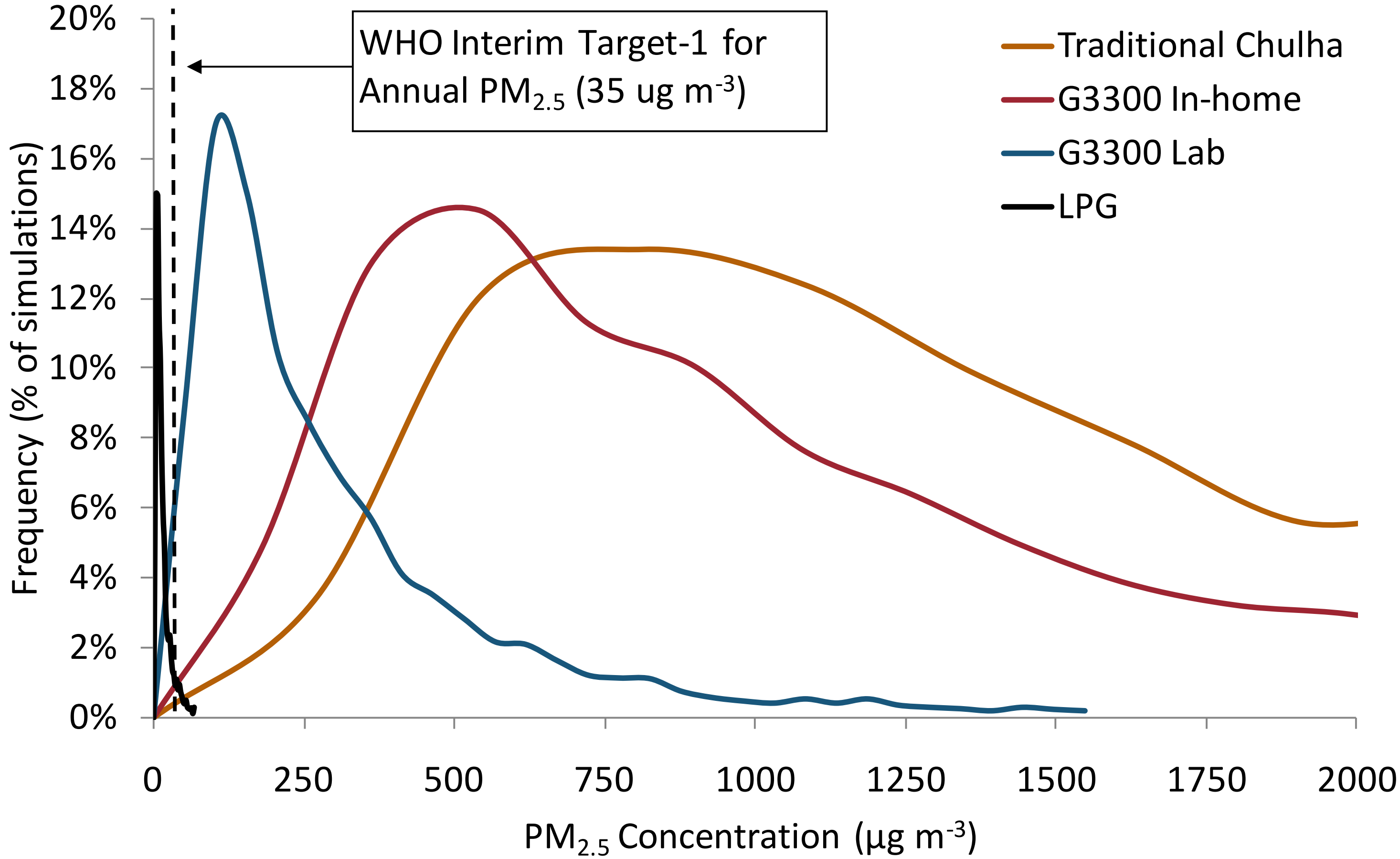
Model Inputs				
Parameter	**Unit**	**Mean**	**Minimum**	**Maximum**
Air exchange rate (α)	hr^{-1}	25	3	60
Kitchen volume (V)	m^3	30	3	100
Fraction of emissions entering room (f)	Unit-less	1.0	-	-
Cooking energy required	MJ-delivered	11#	3	30

•Thermal efficiencies, emission factors, and stove power are all fuel/stove specific.
\# From Habib et al. (2004)

Example of model output simulations for during a single cooking event



Distribution of Model Output of 24-hr Mean $PM_{2.5}$ Concentrations



Model Output Summary and Percent of Simulations Meeting WHO Air Quality Guidelines for Four Fuel-Stove Combinations

	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
Percent of simulations (homes) meeting WHO $PM_{2.5}$ guidelines				
Annual Int 1 (35 $\mu g\ m^{-3}$)	0%	0%	4%	91%
Annual Final (10 $\mu g\ m^{-3}$)	0%	0%	0%	52%

Using the Model to Determine Stove Emission Limits Required to Meet WHO Guidelines

- The model was run in reverse to calculate emission factors (g/MJ-delivered) that would result in kitchen concentrations that met the WHO Guidelines for $PM_{2.5}$ and CO
- Emission limits were determined based on scenarios of 50%, 75%, and 90% meeting WHO guidelines
- Resulting emission factor (g/MJ-delivered) is a combination of how cleanly the stove burns (grams pollutant per kg fuel consumed) and how efficiently it transfers fuel energy to food (thermal efficiency: KJ delivered per KJ in fuel)

Emission factors (g per MJ-delivered) required to meet selected WHO AQGs

% meeting WHO Annual Interim Target-1 $PM_{2.5}$ (35 µg m^{-3})	**50%**	**75%**	**90%**
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

Slightly higher than LPG

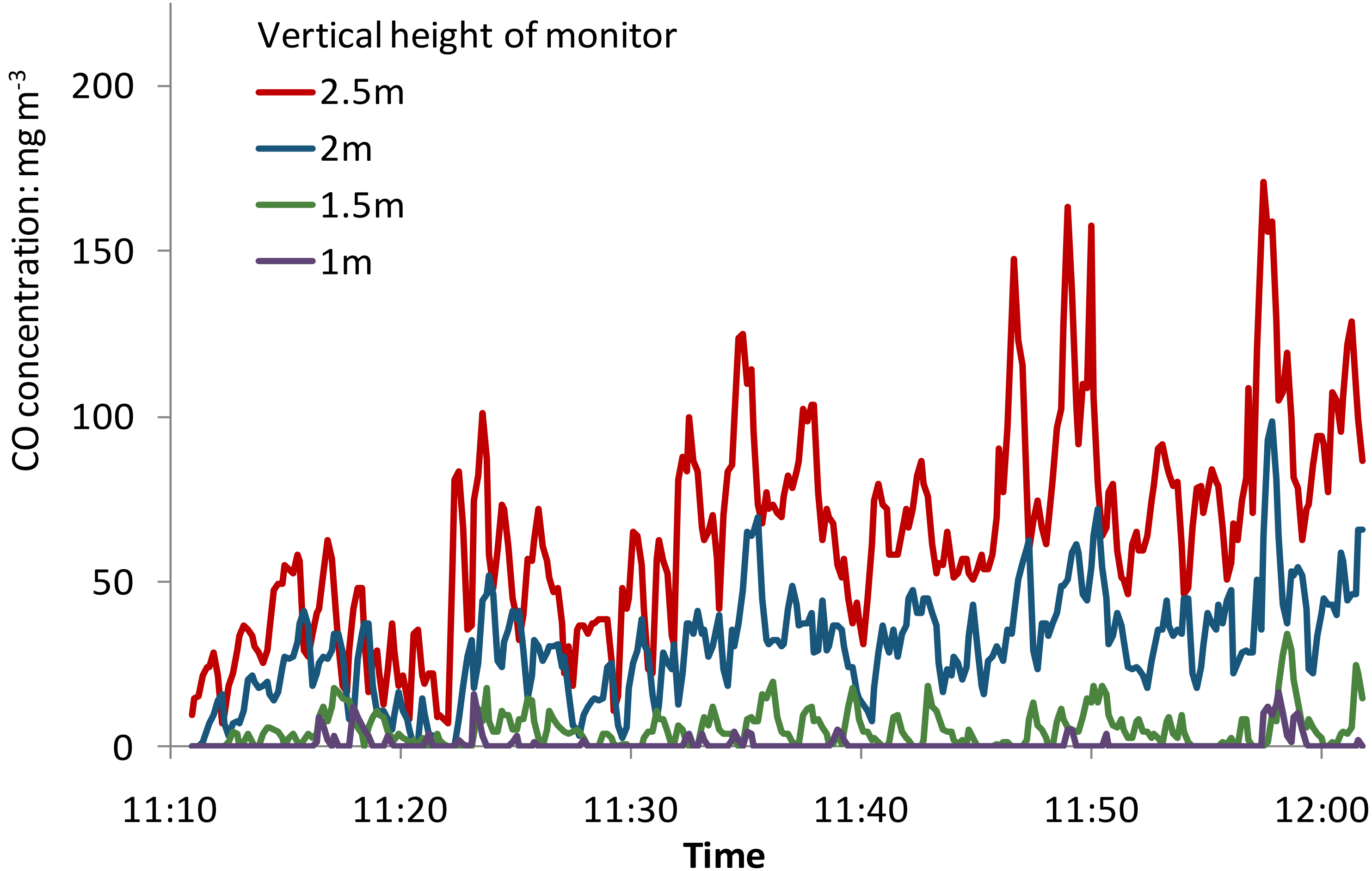
Model Assumptions and Limitations

- Model likely overestimates IAP concentrations (conservative for relating to standards or guidelines)
- Input distributions for daily energy needs, ventilation rates, field-based estimates of emission factors, thermal efficiency, and stove power are based on limited data.
- Assumes all emissions enter room. Stoves are often placed under ventilation windows or openings, which immediately vent considerable fractions of emissions outdoors
- Assumes three events per day on a single stove, split evenly for total required cooking energy (11 MJ).
- Assumes instantaneous mixing of emissions throughout kitchen, while in reality IAP concentrations vary, especially vertically

Testing Model with Field Data from India

- The level of stratification was evaluated in five rural India kitchens during 70 cooking events, for which CO monitors were located across four vertical and four horizontal positions
- The median CO ratio of the highest to lowest positioned monitor was 16, indicating the difficulties using a single concentration to represent the kitchen

Minute-by-Minute CO Concentrations Showing Stratification in an Indian Kitchen



Summary and Future Directions

- Model can be used to predict kitchen concentrations of air pollutants, given emission factors and typical cooking and household parameters.
- Model can determine stove emission limits necessary to meet specific air pollution guidelines indoors.
- The input range can be narrowed to fit a particular setting or widened for a conservative global application.
- Use of such a model during stove development may enable stove programs to better assess when a stove is ready for pilot testing in the field.
- More and better input data (emissions, energy needs, kitchen characteristics, IAP stratification) will help increase the model's accuracy and utility.

Thank you

Contact information:

mjohnson@berkeleyair.com
dpennise@berkeleyair.com
dcharron@berkeleyair.com

www.berkeleyair.com