Indoor Air Quality Impacts of a Woodstove Exchange Program in Washington County, Oregon

Master's Thesis Defense
6/1/2020

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Introduction

- As of 2015 , 11.6 million homes used wood as their primary or secondary fuel source.[1]
- Wood stoves used to heat homes are often old and inefficient[2] these stoves generate particulate matter (PM) that lead to degraded air quality.
- Strong evidence exists that shows indoor levels of PM can adversely affect human health.[3]

References available at end of presentation.

Washington County

- Washington County often ranks as one of the healthiest counties in Oregon.
- Winter-time air quality is some of the worst in the state.
- 1/3 of homes use these old stoves for heating which is a major source of winter-time air pollution.
- Washington County has had $PM_{2.5}$ levels that put the county at risk for violating the federal Clean Air Act.

Wood Stove Exchange Program (WSEP)

- Washington county created an incentive program to help homeowners replace old wood stoves
- Since launching in 2016, 390 stove exchanges have occurred.
- The WSEP estimates this has resulted in a 28 ton reduction in particulate matter and 164 ton reduction of other air pollutants. (CO, VOCs etc)

Project Overview

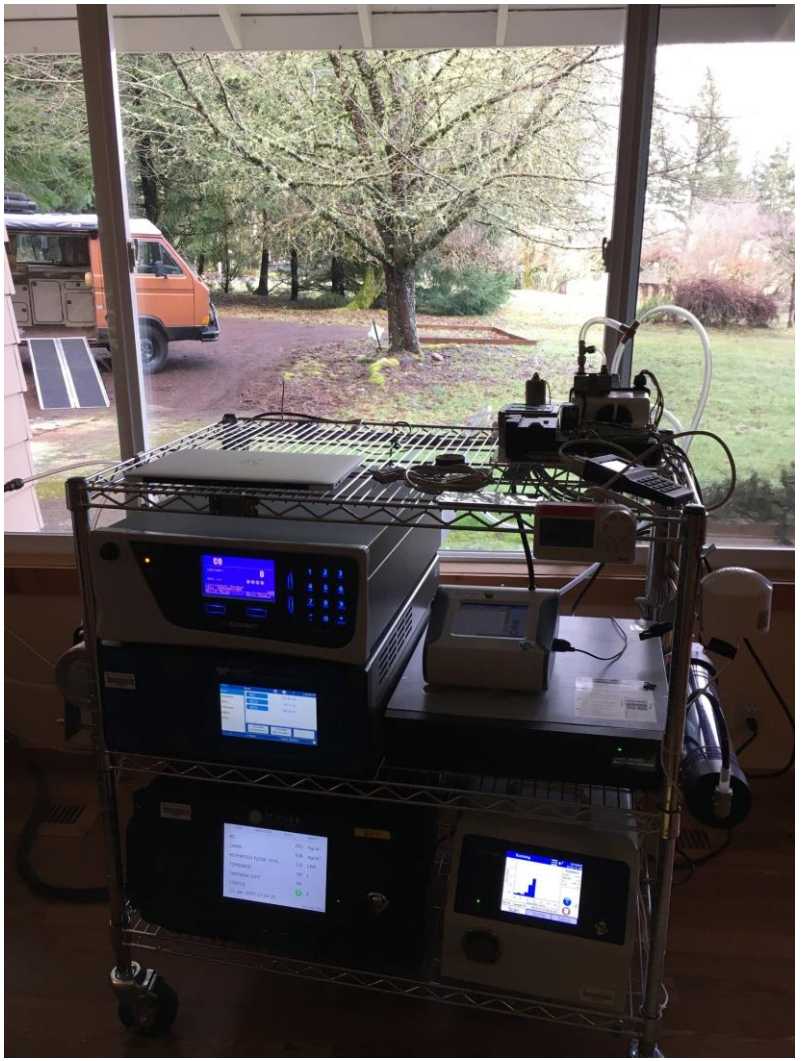
- We coupled with Washington County to monitor air quality before and after a wood stove exchange.
- Investigated correlation of building weatherization (i.e. airtightness)with indoor and household outdoor air pollution levels.
- Attempted to leverage data to identify wood stove $PM_{2.5}$ source strengths.

Scope of Study

1. Will the WSE effect **indoor** levels of air pollution?
2. Will the WSE effect **household outdoor** levels of air pollution?
3. Are periods of **woodstove operation** associated with elevated levels of pollution, inside and around the home?
4. Are **building weatherization** (i.e. airtightness) metrics associated with indoor or household outdoor air pollution levels?

Recruitment of households

- Two requirements for study inclusion
  - Household has an existing woodstove or fireplace
  - New heating source must be a woodstove or ductless heat pump
- Participants were offered a financial incentive to participate in the study.
  - $50 for basic monitoring
  - $200 for enhanced monitoring



Basic air quality monitoring instrumentation

Constituent	Method	Device	Time-resolution	Deployment
PM2.5, PM10	Low cost, light-scattering sensor	PurpleAir PA-II SD	Real-time, <5 min	Entire monitoring period
Stove operation	Temperature sensor/logger	Geocene Dot	Real-time, <5 min	Entire monitoring period
Building airtightness	Whole-house blower door test	Minneapolis Blower Door	Once per home	Once per home
Carbon dioxide	Non-dispersive infrared sensor	Onset MX1102	5 min	Entire monitoring period

PurpleAir II sensor

- Low cost light scattering sensor.
- $PM_{2.5}$ and PM_{10}
- Counts particles in size bins from 0.3 – 10 um
- Often particle counts are within a factor of two compared to research grade equipment.

Stove use monitor

- High temperature sensor and data logger.
- Allowed for AQ data to be filtered for periods when stoves were active.
- Threshold temperatures were chosen for each household, above which stove use was apparent

Blower door test

- Used to conduct a multi-point blower door test.
- Data enables estimation of pressure-flow relationships for each household.
- Also allows for calculation of estimated leakage area.

Methods: CO2 Monitor

- Monitors were setup outside the home and in the common area of the home.

Enhanced air quality monitoring instrumentation

Constituent	Method	Device	Time-resolution	Deployment
Black carbon	5-wavelength aethalometer	Magee Aethalometer	Real-time, 5 minute resolution due to switching valve	3 days pre exchange, 3 days post
Brown carbon (UVPM)	5-wavelength aethalometer	Magee Aethalometer	Real-time, 5 minute resolution due to switching valve	3 days pre exchange, 3 days post
Carbon monoxide	Non-dispersive infrared with filter correlation	Ecotech Serinus 30 CO monitor	Real-time, 5 minute resolution due to switching valve	3 days pre exchange, 3 days post

Brown and black carbon

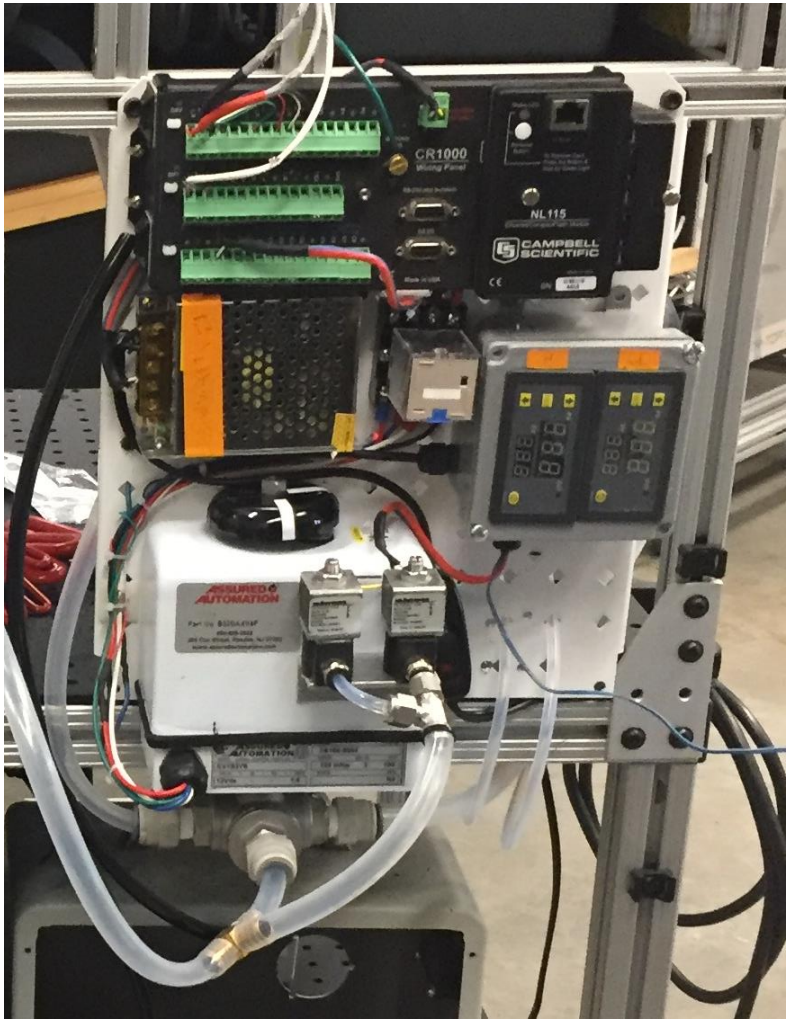
- Black carbon measured by light attenuation at 880nm.
  - Indicates fossil fuel burning
- Brown carbon proxy (UVPM) measured by attenuation at 370nm.
  - Indicates biomass combustion

Carbon monoxide

- Uses a nondispersive infrared sensor to detect CO
- Analyzer was factory calibrated prior to field deployment.

Switching valve

- One set of instruments can sample both inside and outside if the sampling port is switched.
- A switching valve for particle and gas phase constituents was developed.
- Location duration was 5 minutes.



Methods: Estimation of WSE impacts on indoor and household outdoor pollution (1/4)

Challenges

- Presumably more efficient woodstoves emit few air pollutants.
- In field studies many variables cannot be controlled, and the **households** in this study are engaging in behaviors and **activities that are variant in time**.
- Additionally regional **ambient background levels of air pollution fluctuate** on diurnal, weekly, and seasonal time-scales.
- A variety of empirical approaches were taken here as a first step in developing an understanding of the WSEs impact on local and indoor air quality.

Methods: Estimation of WSE impacts on indoor and household outdoor pollution (2/4)

Local Outdoor

- Pre and post exchange levels of outdoor $PM_{2.5}$ were measured directly using a PurpleAir sensor attached to the outside of the home.
- This comparison should be interpreted cautiously, as background levels of air pollution changed over the course of the study for many deployments.

Methods: Estimation of WSE impacts on indoor and household outdoor pollution (2/4)

Indoor

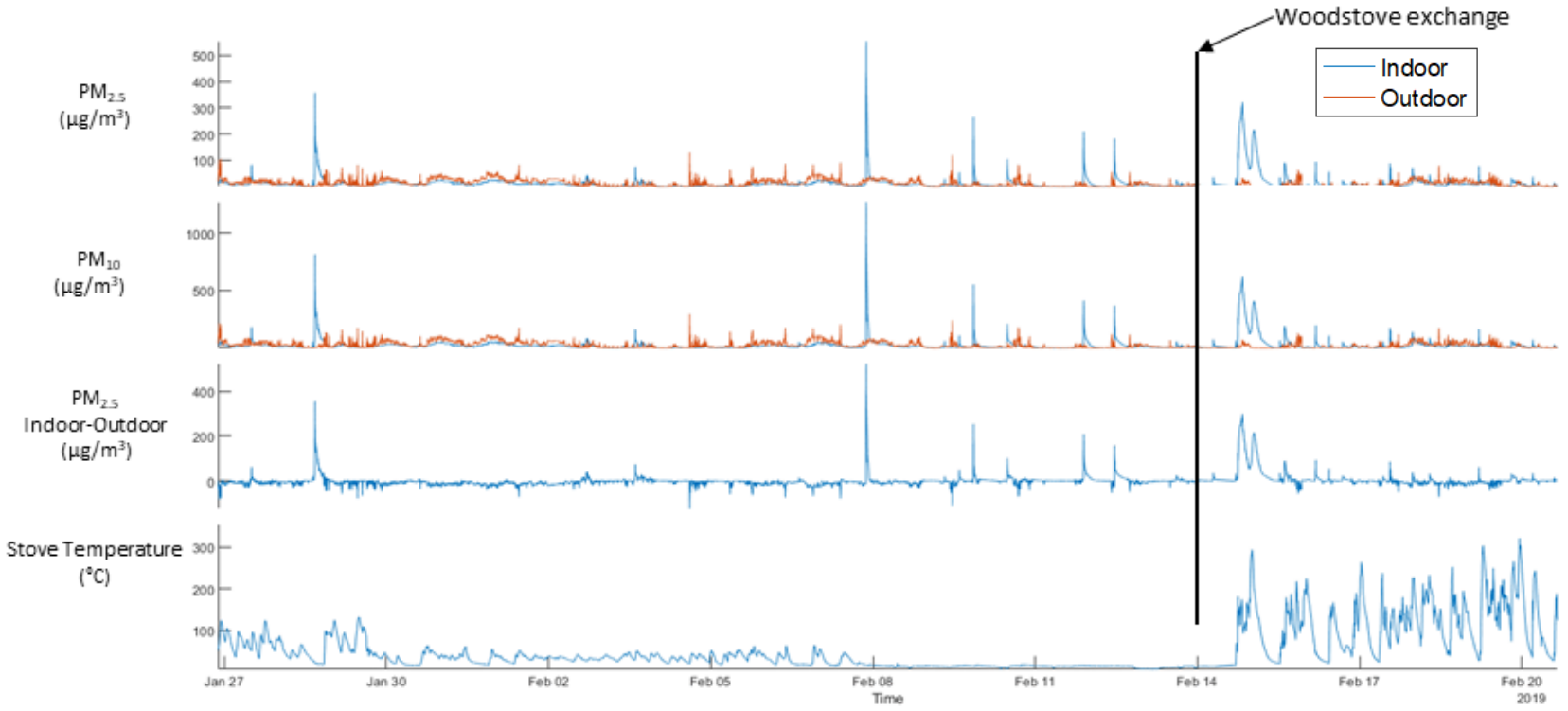
- Similarly absolute levels of $PM_{2.5}$ pre and post exchange inside the home were measured.
- From the perspective of exposure, this metric is a direct representation of whether the woodstove exchange program reduced exposures to air pollution.

Comparison

- Comparing indoor and outdoor levels of pollution may be the most effective method in determining the effect of the WSE
- Indoor-outdoor comparison allow for effect of background pollution changes to be minimized

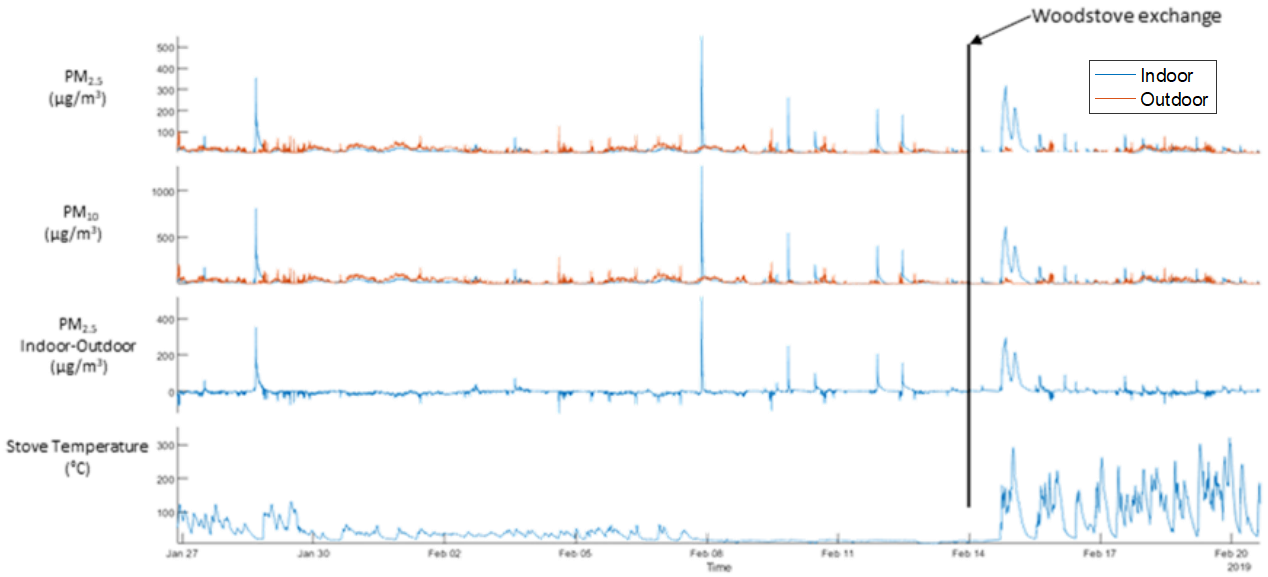
$$\Delta C = C_{indoor} - C_{outdoor}$$

Air Monitoring Results: Time-series data (basic monitoring)



Home B-6

Air Monitoring Results: Time-series data (basic monitoring)

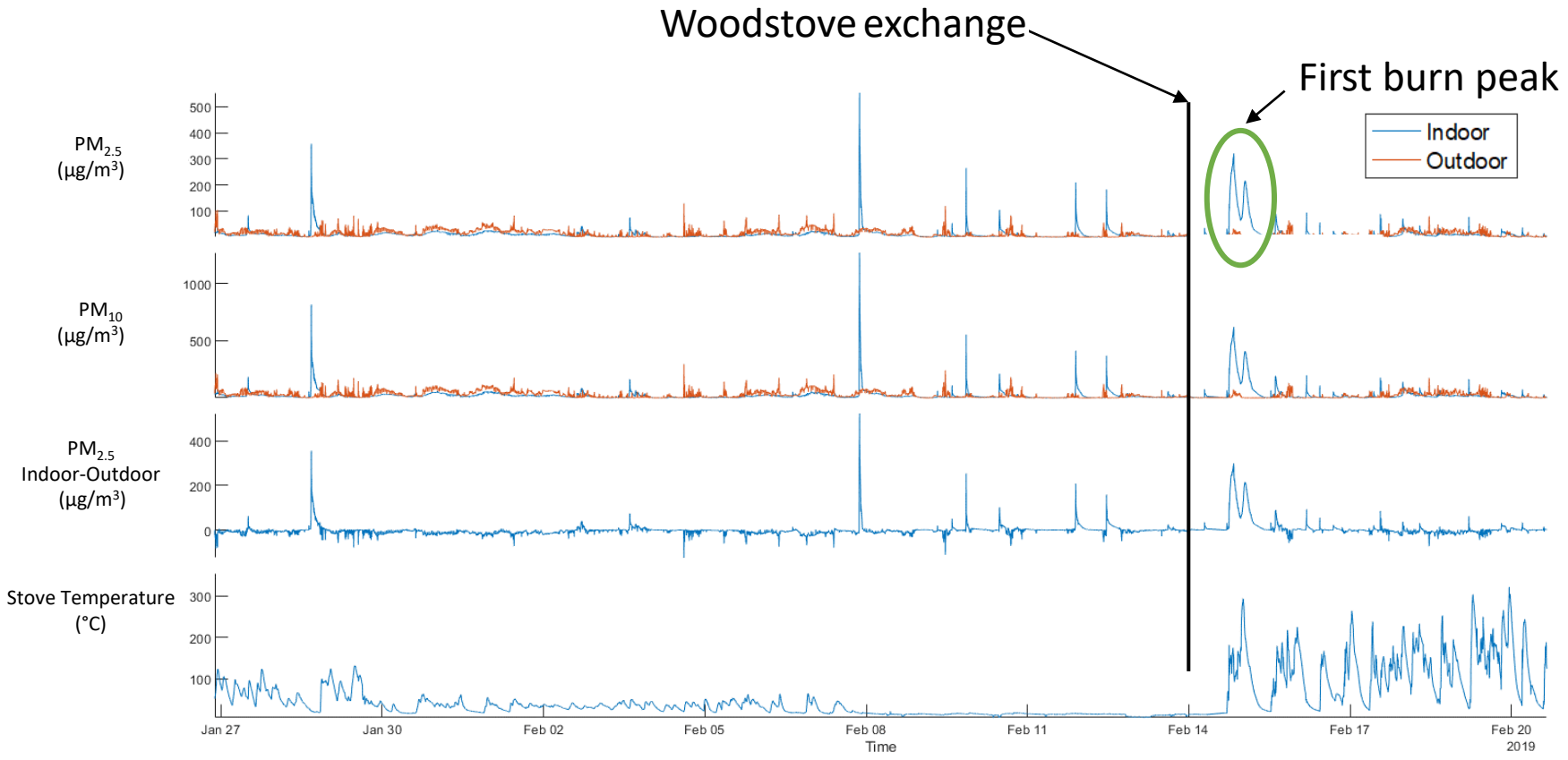


"Good" air quality as below 12ug/m^3 $PM_{2.5}$

"Safe" $PM_{2.5}$ over a 24hr period is 35ug/m^3

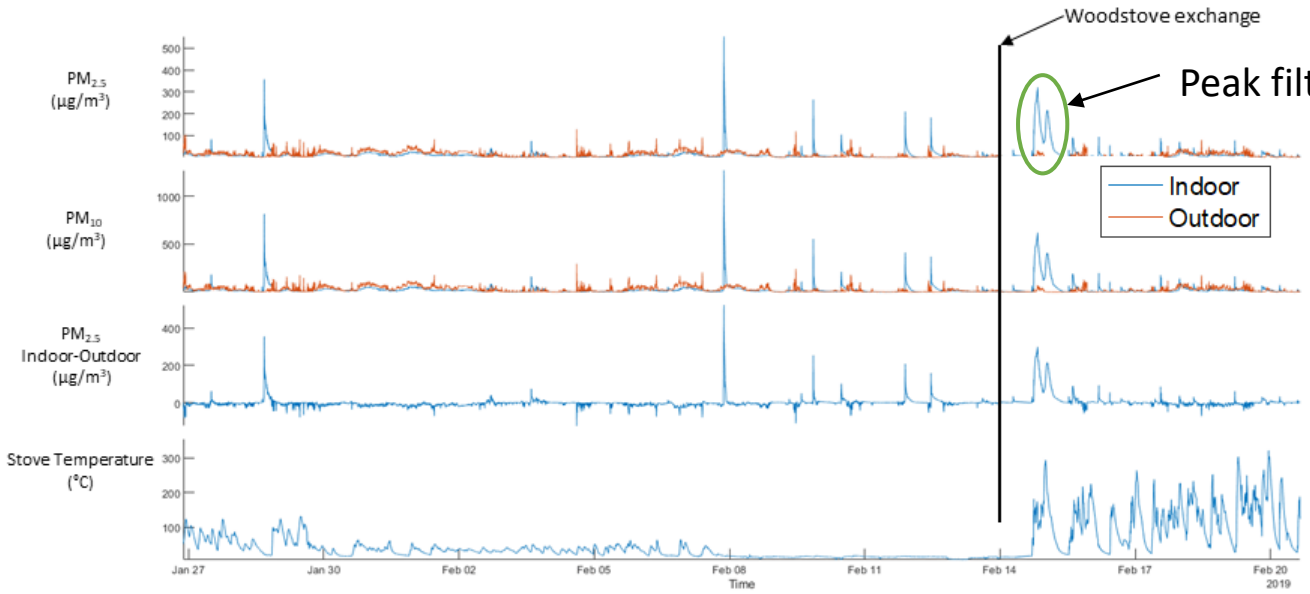
	Median outdoor $PM_{2.5}$ (µg/m^3)			Median indoor $PM_{2.5}$ (µg/m^3)		
	Pre-exchange	Post-exchange	Change	Pre-exchange	Post-exchange	Change
No Filtering	4.6	4.9	0.3	4.6	4.8	0.2

Air Monitoring Results: Time-series data (first burn peak removed)



Home B-6

Air Monitoring Results: Time-series data (first burn removed)



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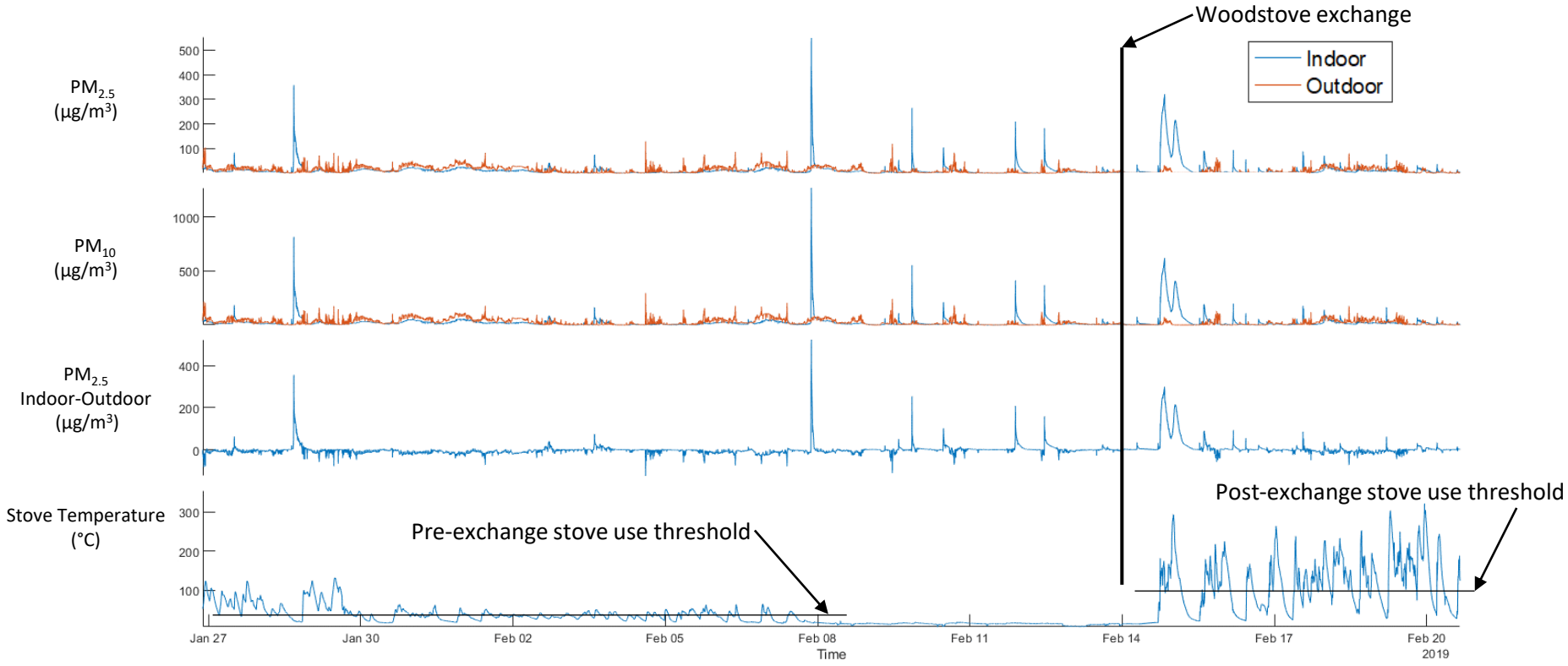
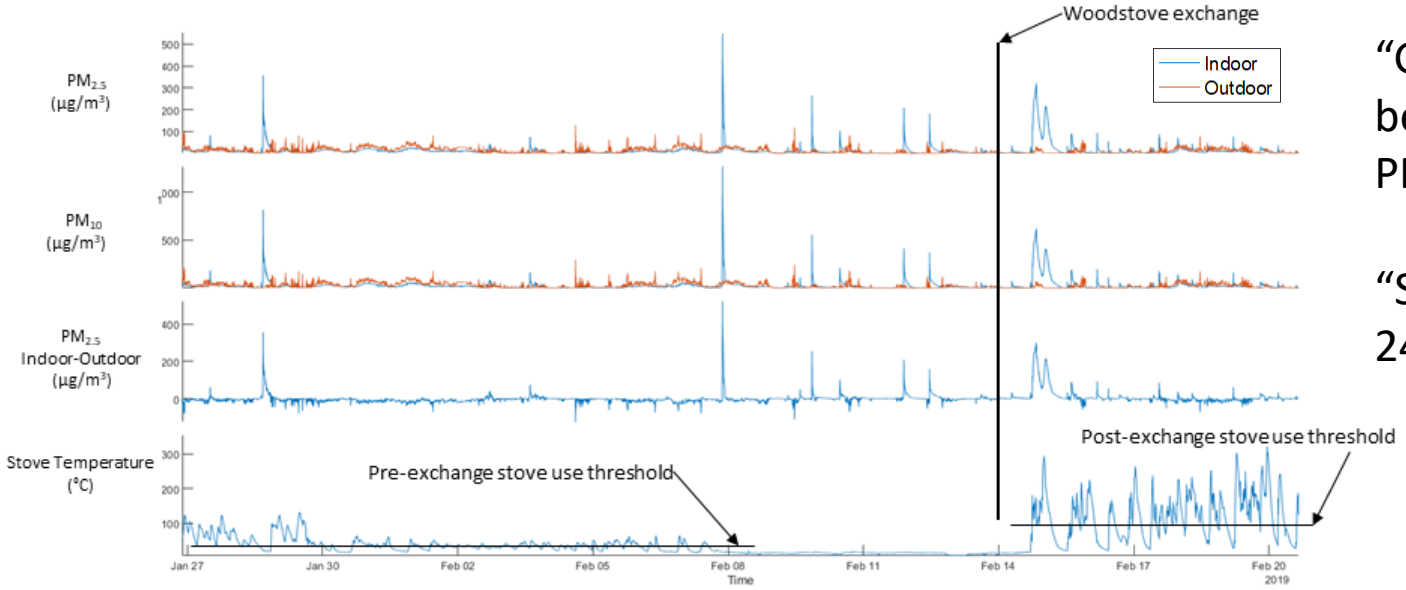
	Pre-exchange	Post-exchange	Change	Pre-exchange	Post-exchange	Change
No Filtering	4.6	4.9	0.3	4.6	4.8	0.2
First burn removed				4.6	4.3	-0.3

Air Monitoring Results: Time-series with stove usage



Home B-6

Air Monitoring Results: Comparison of $PM_{2.5}$ pre and post exchange

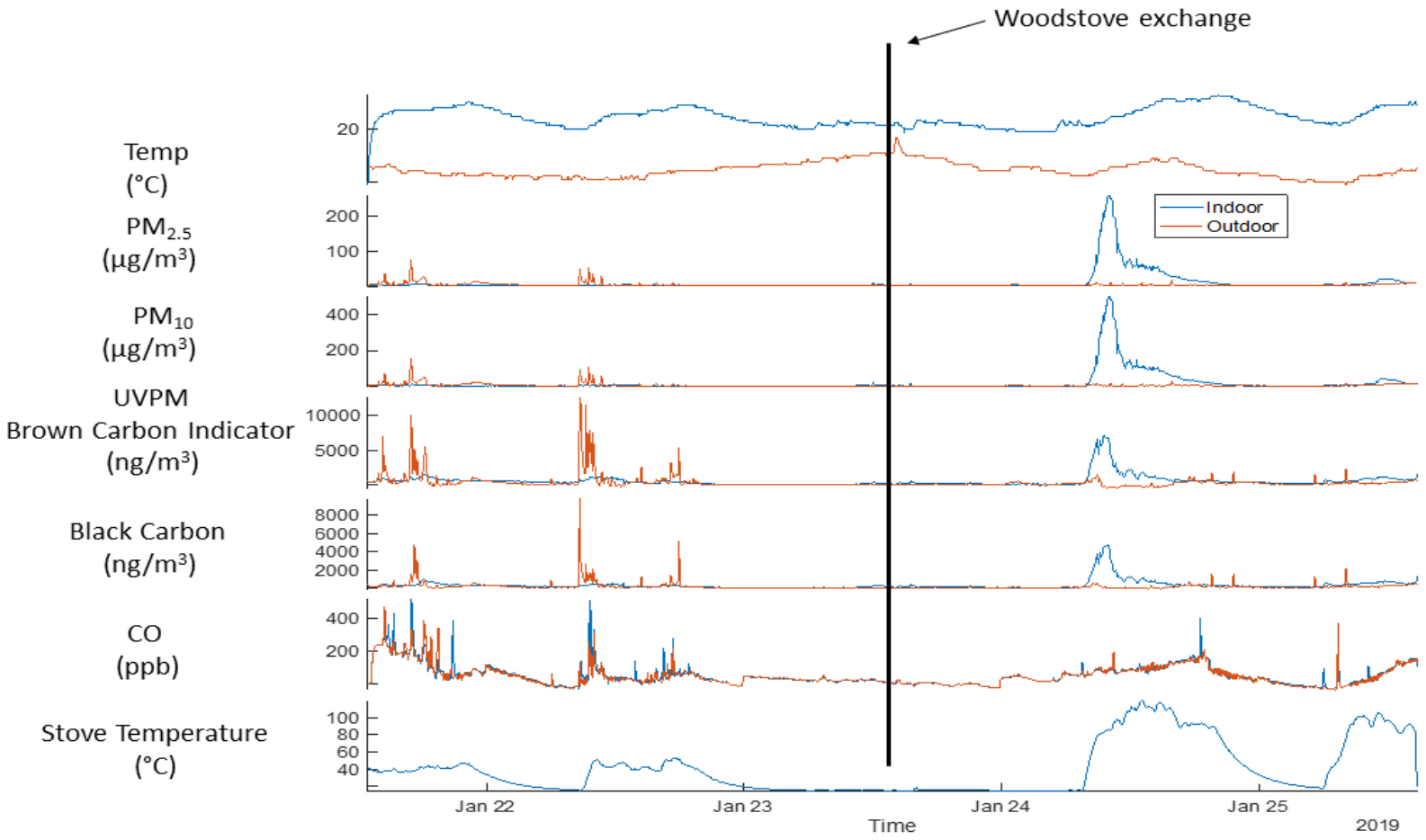


"Good" air quality as below 12µg/m³ $PM_{2.5}$

"Safe" $PM_{2.5}$ over a 24hr period is 35µg/m³

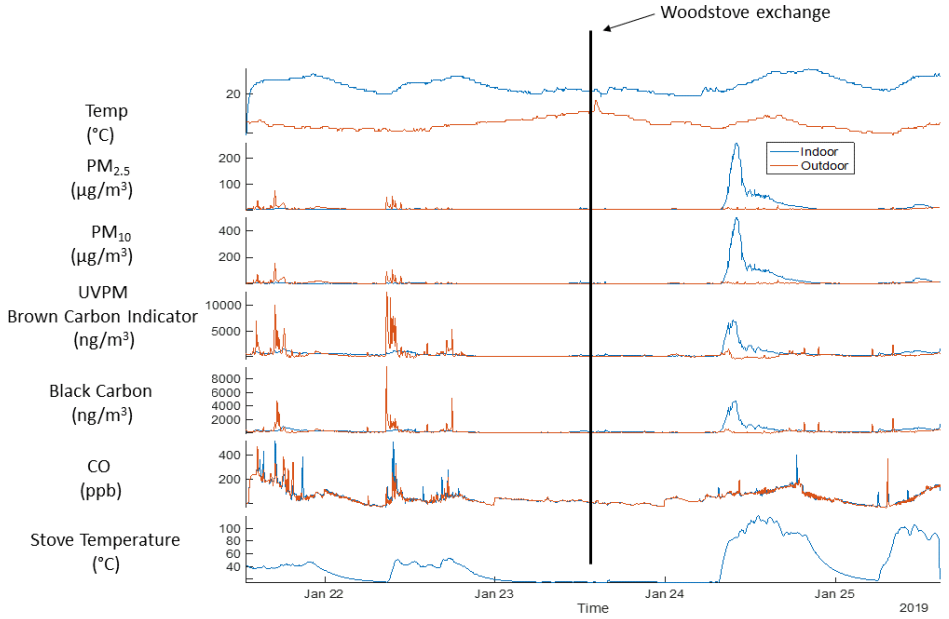
	Median outdoor $PM_{2.5}$ (µg/m³)			Median indoor $PM_{2.5}$ (µg/m³)		
	Pre-exchange	Post-exchange	Change	Pre-exchange	Post-exchange	Change
No Filtering	4.6	4.9	0.3	4.6	4.8	0.2
First burn removed				4.6	4.3	-0.3
Stove on, first burn removed	5.4	5.9	0.5	5.3	4.7	-0.6

Air Monitoring Results: Time-series data (enhanced monitoring)



Home E-32

Air Monitoring Results: Time-series data (enhanced monitoring)

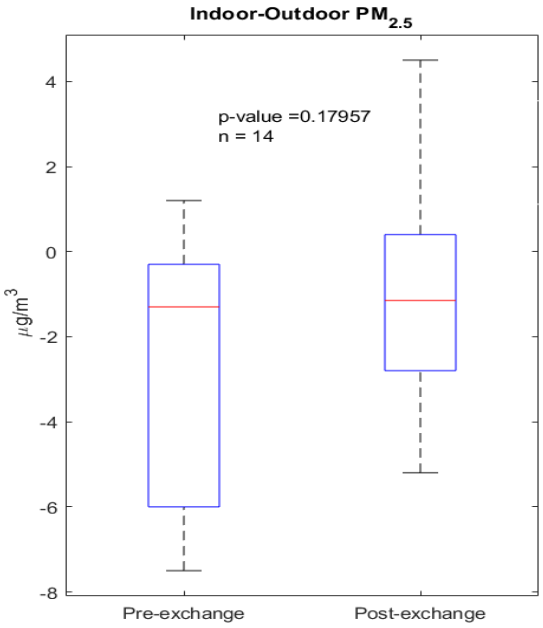


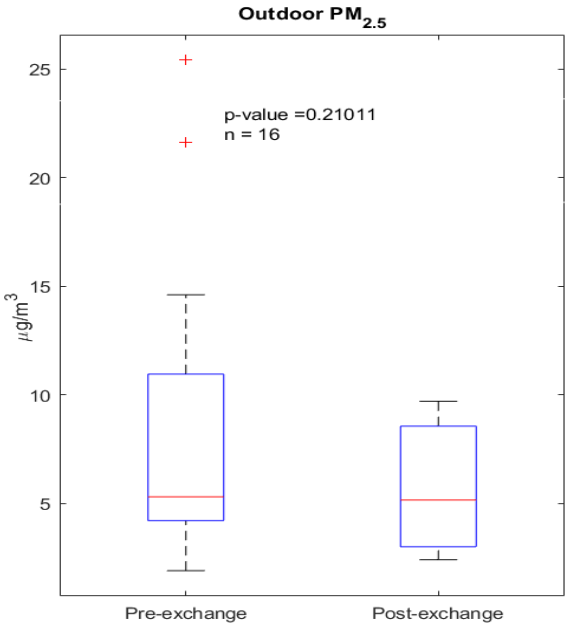
Oregon Ambient Benchmark
Black Carbon 100ng/m³

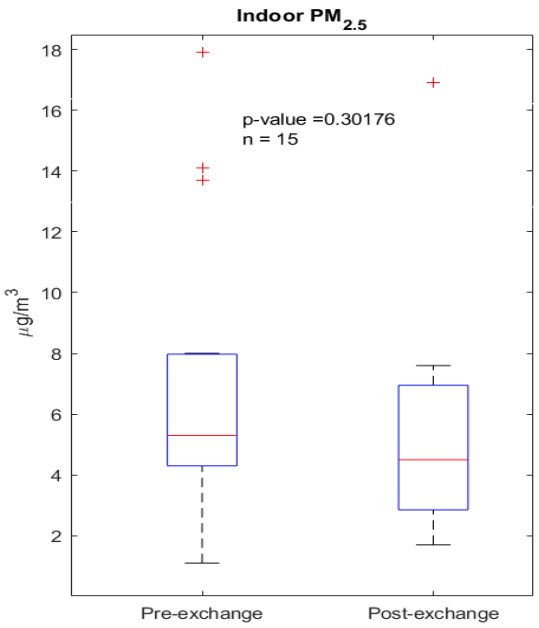
NIOSH 15 minute Short Term Exposure Limit
CO 200ppm

	Average Outdoor			Average Indoor		
During periods of stove use	Pre-exchange	Post-exchange	Δ	Pre-exchange	Post-exchange	Δ
Br. Carbon Indicator (ng/m³)	1340	790	-550	1060	870	-190
Black Carbon (ng/m³)	950	430	-520	540	470	-70
CO (ppm)	200	150	-50	190	170	-20

Bulk statistical analysis







Is data normally distributed?

No

Are differences between pre and post exchange median values statistically significant?

For the non-parametric data a sign test was conducted for all pre-post differences.

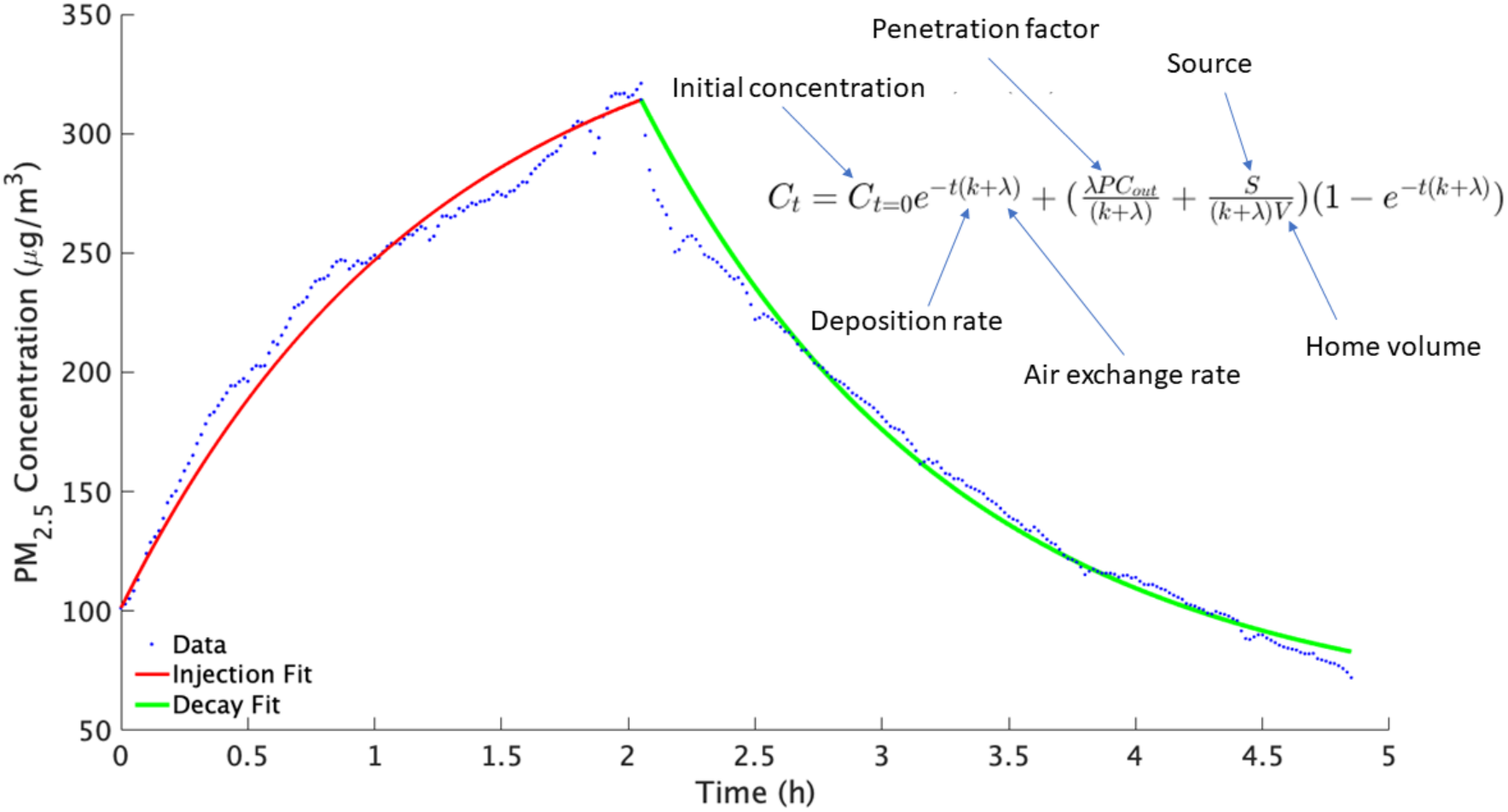
The differences observed were not statistically significant.

Stove $PM_{2.5}$ source strength analysis

- 13 of 17 homes with data available exhibited large transient $PM_{2.5}$ peaks associated with the first burn of the new stove.
- This discovery was an opportunity to investigate particle source and sink mechanisms.
- Applied mass-balance principles to the substantial elevation and subsequent decay of indoor $PM_{2.5}$

$$\frac{dC_{in}}{dt} = -\lambda C_{in} + \lambda C_{out} + S/V$$

Stove $PM_{2.5}$ source strength analysis



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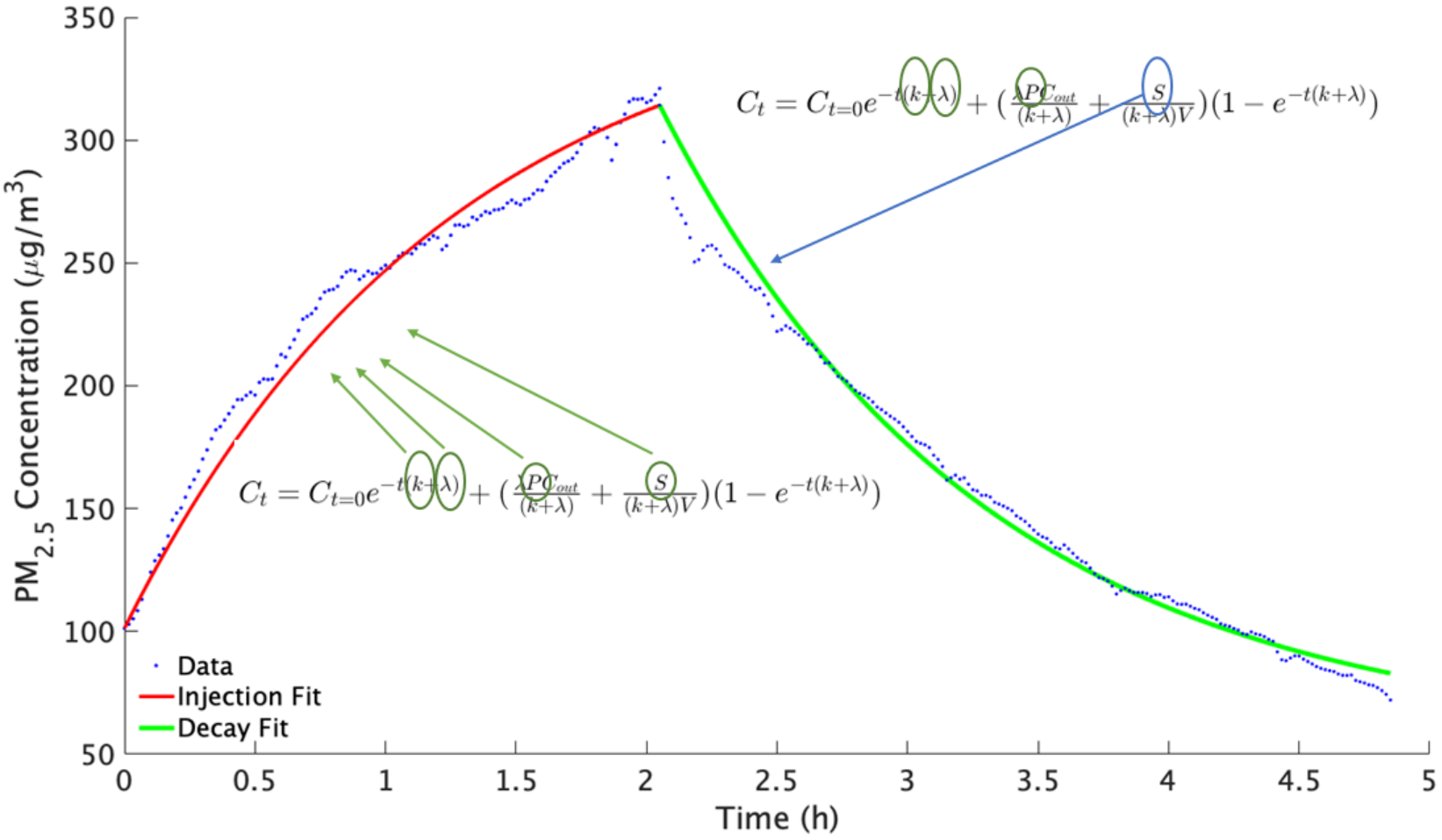
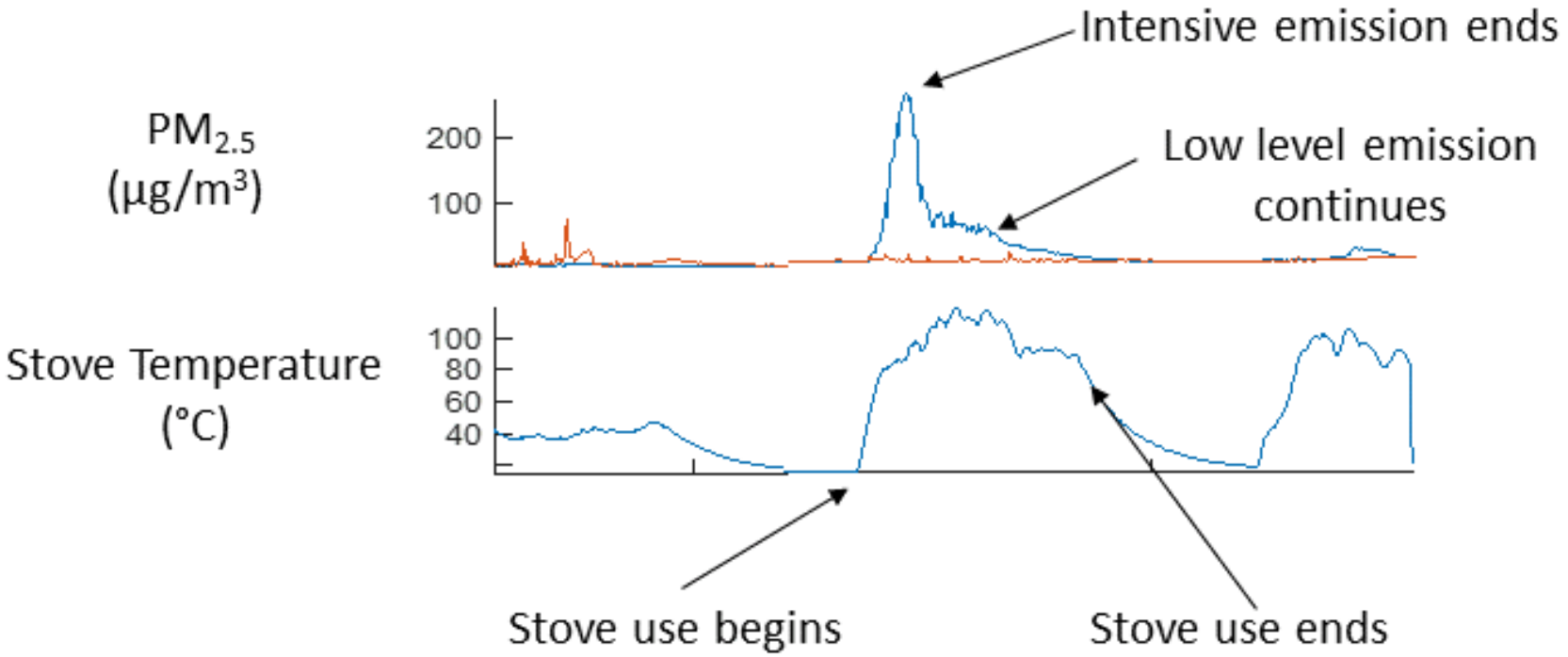
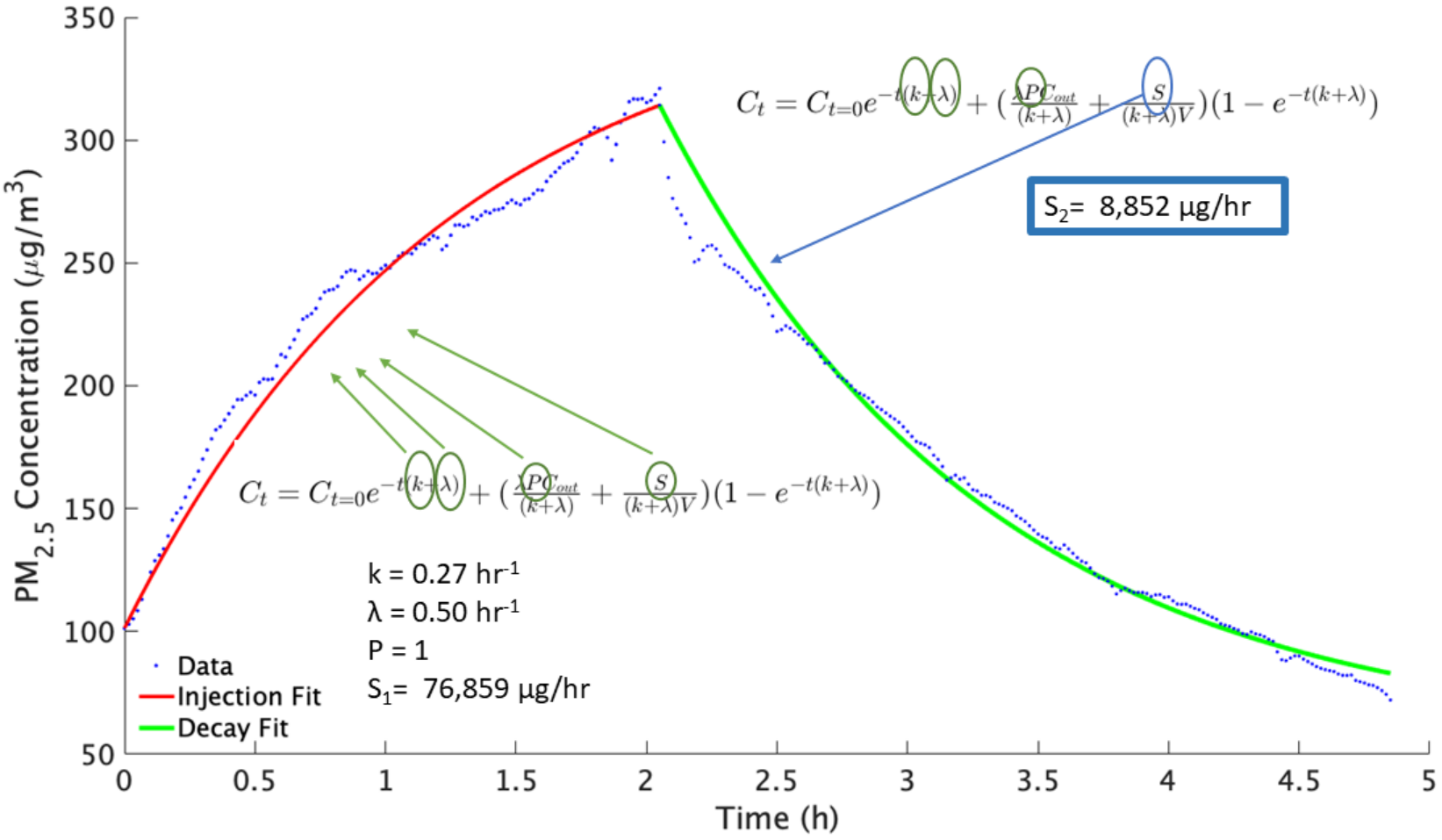


Stove $PM_{2.5}$ source strength analysis

S_1 vs S_2



Stove $PM_{2.5}$ source strength analysis



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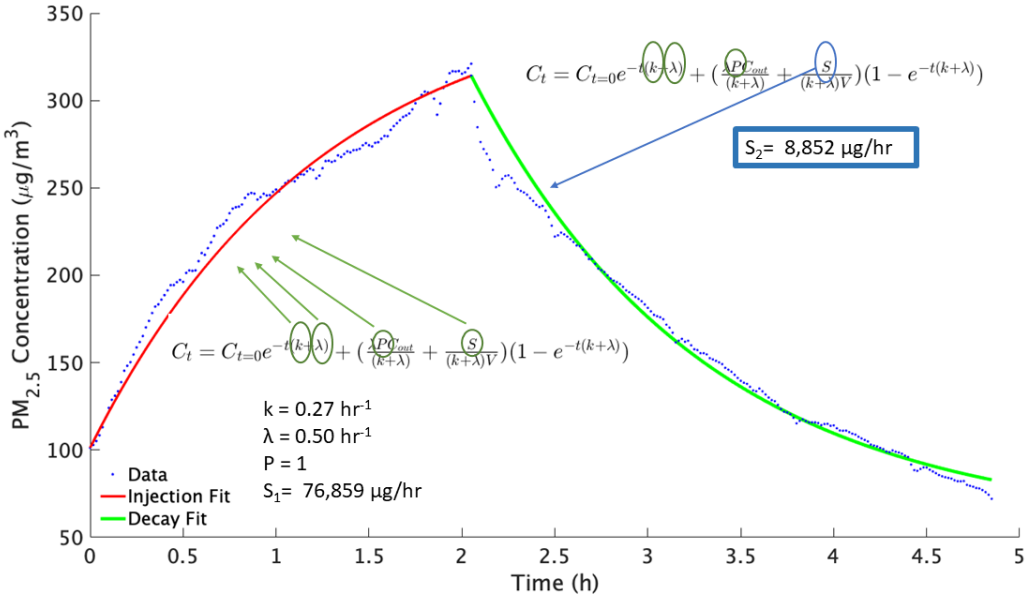
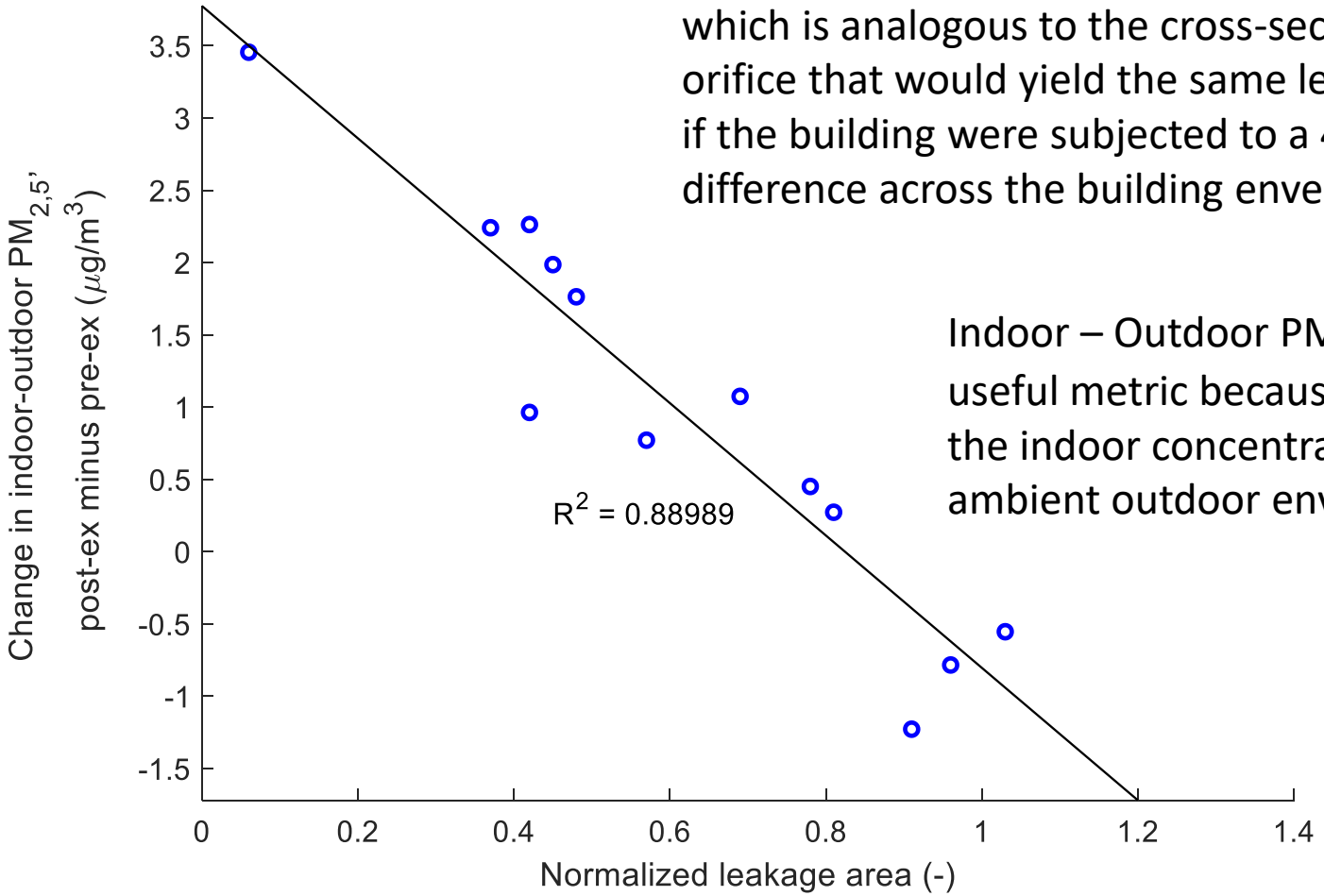


Home	Penetration Factor	Loss Coefficient K (hr^{-1})	λ (hr^{-1})	S_1 Emission Peak Source Strength (µg/h)	S_2 Normal Operation Source Strength (µg/h)
B-6	0.23	0.27	0.5	76,859	8,852
B-10	0.99	0.00	0.7	20,702	9,432
B-11	0.84	1.24	0.84	71,619	13,078
E-31	1.00	1.01	0.53	125,630	23,304

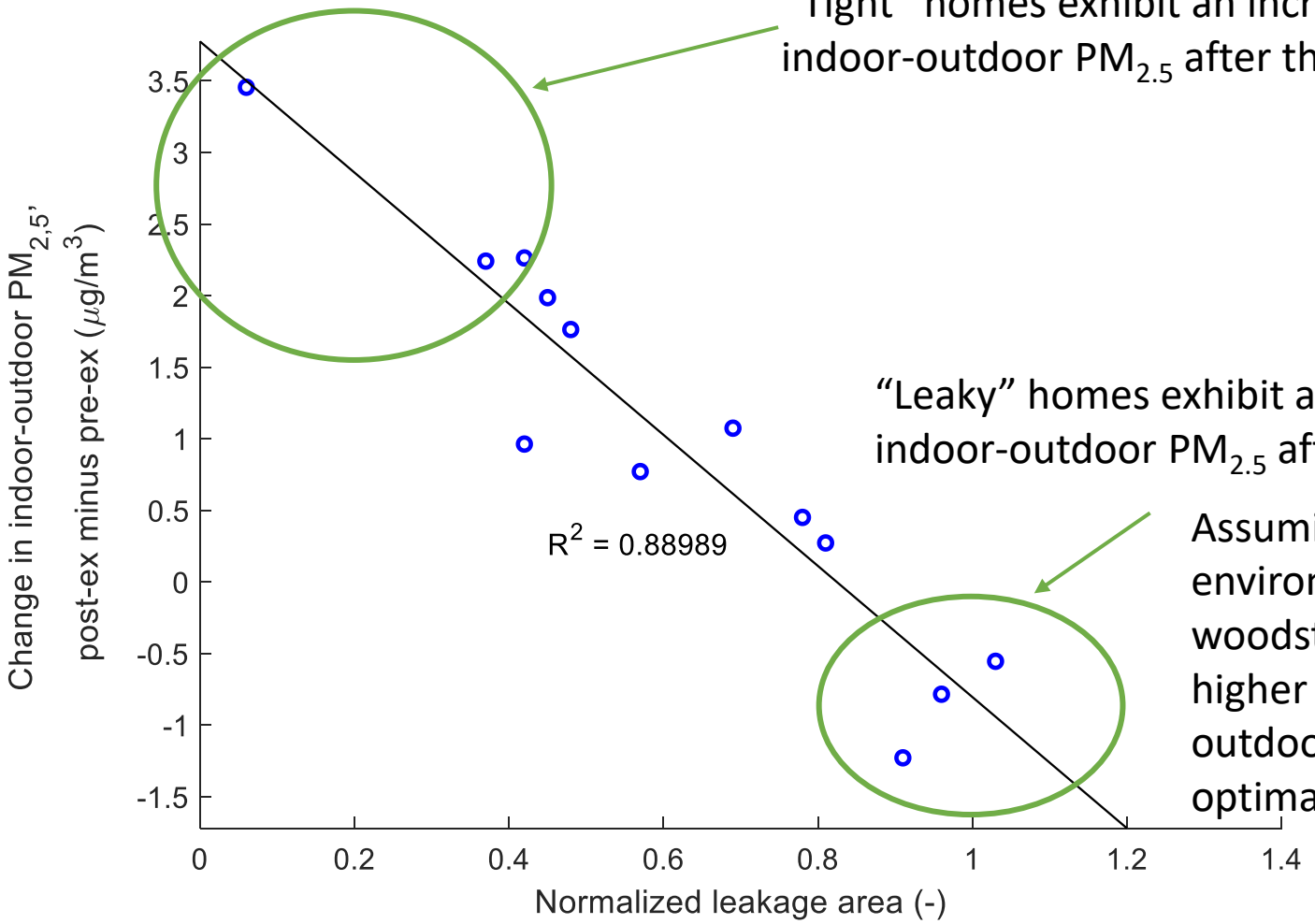
Correlation between normalized leakage area (NLA) and changes in $PM_{2.5}$



NLA is derived from the estimated leakage area (ELA) which is analogous to the cross-sectional area of an orifice that would yield the same leakage flow rate as if the building were subjected to a 4 Pa pressure difference across the building envelope.

Indoor – Outdoor $PM_{2.5}$ ($\Delta C_{PM_{2.5}}$) is a useful metric because it normalizes the indoor concentration to the ambient outdoor environment.

Correlation between normalized leakage area (NLA) and changes in $PM_{2.5}$



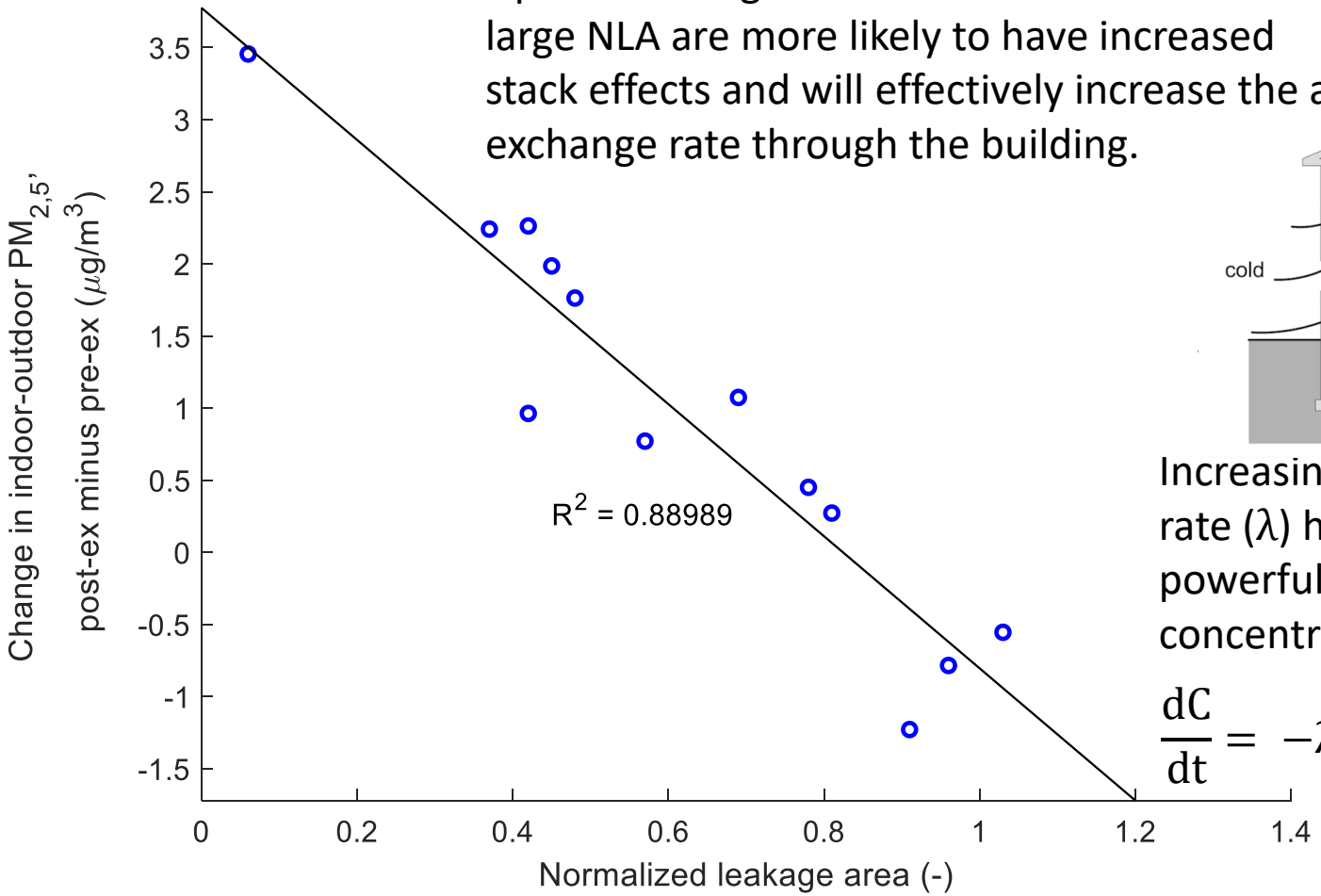
"Tight" homes exhibit an increase in the indoor-outdoor $PM_{2.5}$ after the exchange.

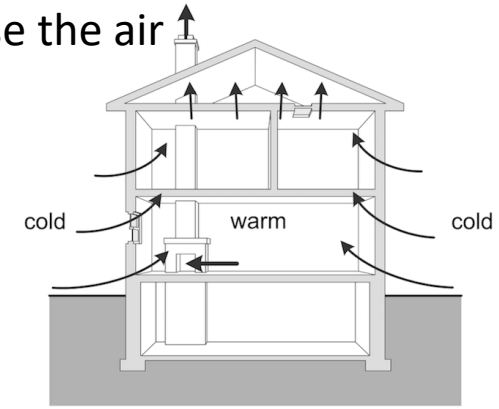
"Leaky" homes exhibit a decrease in the indoor-outdoor $PM_{2.5}$ after the exchange.

Assuming that indoor environments during woodstove operation are higher in $PM_{2.5}$ than outdoor, a reduction is a optimal.

Correlation between normalized leakage area (NLA) and changes in $PM_{2.5}$

Upon receiving a new woodstove homes with a large NLA are more likely to have increased stack effects and will effectively increase the air exchange rate through the building.





Increasing the air exchange rate (λ) has a direct and powerful effect on indoor concentration of pollutants.

$$\frac{dC}{dt} = -\lambda C + \lambda C_{out} + S/V$$

Key Findings

- For 13 of 17 homes, large transient peaks of $PM_{2.5}$ were observed following the first stove use.
- Depending on method of comparison different number of homes showed a reduction in indoor $PM_{2.5}$
  - Including all data 7 homes showed reductions.
  - Excluding periods of stove inactivity, 12 homes showed reductions.
  - Excluding periods of stove inactivity and first burn peaks, 12 homes showed reductions.
- Differences in median $PM_{2.5}$ are not statistically significant
- Air tightness is anti-correlated with $\Delta C_{PM_{2.5}}$, implying homes with high ventilation removed indoor emissions from the woodstoves.
- For 4 homes studied, normal stove operation resulted in $PM_{2.5}$ source strengths on the magnitude of normal household activities.

Limitations

- Homeowner instrument interference resulted in data loss
- Short heating season limited number of homes participating and amount of data gathered.
- Loud machines dissuaded some homeowners from participating in the enhanced monitoring.

Future work

- Stove source strength analysis should continue across more homes.
- Since homeowner stove use habits can result in large emission events, a comparison of pre and post source strength could occur for each stove exchange.

Questions?

Blower door test (1/3)

Pressure-flow relationships were log transformed and plotted to determine the air leakage coefficient, C ($m^3/s/Pa^n$), and the pressure exponent, n (-), of each house from a least squares regression fit of the linearaized equation below.

$$\log Q = \log C + n \log \Delta P$$

From this the typically reported metric, air changes per hour at 50 Pa was interpolated. This value is known as the ACH_{50}.

Appendix A: Blower door test (2/3)

- The estimated leakage area, ELA (m^2) is the cross-sectional area of an orifice that would yield the same leakage flow rate as the building if subjected to a 4 Pa pressure difference.
- This value can be used in the Lawrence Berkeley National Laboratory infiltration model to estimate infiltration from the indoor-outdoor pressure difference or from environmental conditions like local wind speeds and indoor-outdoor temperature differences.
- The ELA value was calculated from the previously defined C and n and a reference pressure difference, P_r, of 4 Pa by using the equation below.

$$\mathrm{ELA} = \sqrt{\frac{\rho}{2}}\, C \Delta P_r^{\,n-0.5}$$

Appendix A: Blower door test (3/3)

Normalized leakage (NL, -) was calculated from the effective leakage area, using the following equation developed by the Lawrence Berkeley National Laboratory and as described in ASHRAE Standard 119. H and Href are ceiling height and a reference height respectively.

$$\mathrm{NL} = 1000 \times \left(\frac{\mathrm{ELA}}{\mathrm{A_{floor}}}\right)\left(\frac{\mathrm{H}}{\mathrm{Href}}\right)^{0.3}$$

References

(1) EIA, “Residential Energy Consumption Survey (RECS) - Data - U.S. Energy Information Administration (EIA),” 2015. https://www.eia.gov/consumption/residential/data/2009/ (accessed Jan. 15, 2018).

(2) US EPA, “Burn Wise - Changeout Guide,” *US EPA*, May 22, 2013. https://www.epa.gov/burnwise/burn-wise-changeout-guide (accessed Jan. 15, 2018).(3) Semmens et al 2015

(3) Semmens, E. O.; Noonan, C. W.; Allen, R. W.; Weiler, E. C.; Ward, T. J. Indoor Particulate Matter in Rural, Wood Stove Heated Homes. Environ Res 2015, 138, 93–100.