U.S. EPA "State of VI Science" Workshop

How Vapor Intrusion Data Measured by Communities and Supported by Regulators Can Create "Soil Gas Safe Communities"

Summary of Relevant Vapor Intrusion (VI) Indicator and Tracer (I&T) Research: Recently Completed, On-going & Planned

Chris Lutes and Laurent Levy, Jacobs
A.J. Kondash, RTI International
Chase Holton, Geosyntec

31st Annual International Conference on Soil, Water, Energy, and Air, A Virtual Conference, March 15, 2022

Presentation archived at https://iavi.rti.org/

Presentation Outline

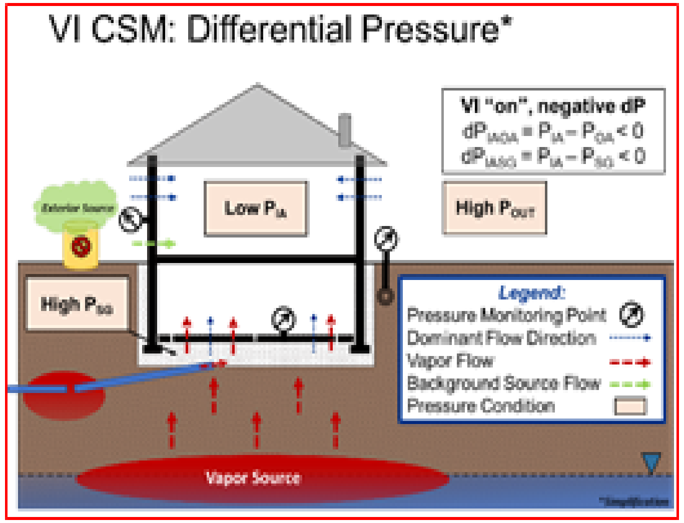
- Fact sheets on radon, temperature and pressure as indicators and tracers are available
- Data sets analyzed – site characteristics
- Review of results of six different data analysis methods

EPA Guidance and Fact Sheets on I&T

- EPA (2015) VI Guidance
  - Buildings with radon greater in indoor air than ambient (outdoor) air are likely susceptible to soil gas intrusion…
  - Pressure differences during sampling (indoor to outdoor or indoor to subslab) can support insights about driving forces
  - EPA recommends documenting wind direction, precipitation information, temperature, barometric pressure
- EPA ITS Fact Sheets (2020)
  - *Monitoring Radon as a VI Tracer or Surrogate*
  - *Measuring Pressure (Differential and Barometric) as a VI Indicator*
  - *Measuring Temperature as an Indicator for VI*

https://iavi.rti.org/assets/docs/Temp_Measurement_Fact_Sheet_int.pdf
https://iavi.rti.org/assets/docs/Pressure_Measurement_Fact_Sheet_Int.pdf
https://iavi.rti.org/assets/docs/Radon_methods_fact_sheet_int.pdf

Example of Fact Sheet Content



Measuring Pressure (Differential and Barometric) as a Vapor Intrusion (VI) Indicator

What Pressures?

- Differential pressure (ΔP)—Difference in pressure between two points in space (indoor/outdoor or indoor/subslab).
- Change in barometric pressure (ΔBP)—Pressure in the atmosphere (indoor and outdoor), change in BP over time is most important (Figure 1).
- Normal changes in BP can be quite large and create pressure differentials across the building envelope if all else is equal (Figure 2). A regular diurnal variation of up to 300 pascals (Pa) is common and weather fronts can cause BP to change by 1,000 Pa over several days.
- Falling BP leads to vapors flowing out of the ground as pressures seek to equalize, but with a time delay.
- Wind loads and stack effects are also important causes of BP variations.

Figure 5. Example Micromanometers

Where to Measure Indoor Leg of Differential Pressure?

- ΔP sensor/recorder should be located on surface/wall with little to no vibration.
- Minimize tubing length (to avoid trip hazard, loss of accuracy).
- Select reference points that can be easily repeated, at a similar elevation.
- Barometric pressure to the accuracy that it is usually measured will be the same inside and outside.

Where to Measure Outdoor Leg of Differential Pressure?

- Seal around tubing that crosses through window, door, or wall.
- Shield outdoor probe from the direct influence of the wind, for example placed pointing toward the ground inside an overturned flower pot or protected by a diffuser (e.g., fish tank bubbler).

Where to Measure Subslab or Outside Basement Foundation Leg of Differential Pressure?

- Install subslab (or below grade wall) ports in each major foundation section, away from utilities and at least a foot from exterior walls. Expect spatial variability—install at least two subslab ports in even a small building.
- Leak test subslab ports with water dam or helium tracer.

Long Term VOC Data Sets:

Sun Devil Manor

Indianapolis (2 floors)

VA Site A (2 zones)

Gaffney

MEW

Simultaneous Indicators and Tracer Data:

VOCs

Radon (indoor vs. outdoor)

Exterior Temperature or Differential Temperature (inside/outside)

Differential Pressure (Subslab vs. indoor or indoor vs. outdoor)

Analysis Tools:

XY Analysis

2x2 Table (Screening)

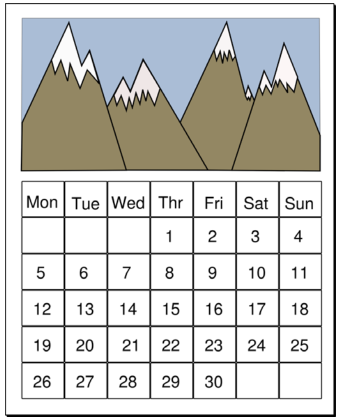
Graphical Temporal Analysis

Time Series Analysis

Peak Value Prediction

Sampling Strategy Performance

Equivalent Protection ($)



High Frequency Data Sets Generally Summarized As Either One Day or One Week Before Analysis

2x2 Table Example

	Diseased	Not Diseased
Test Positive	132	983
Test Negative	45	63,650

2x2 Table example from https://sphweb.bumc.bu.edu/otlt/mph-modules/ep/ep713_screening/EP713_Screening3.html

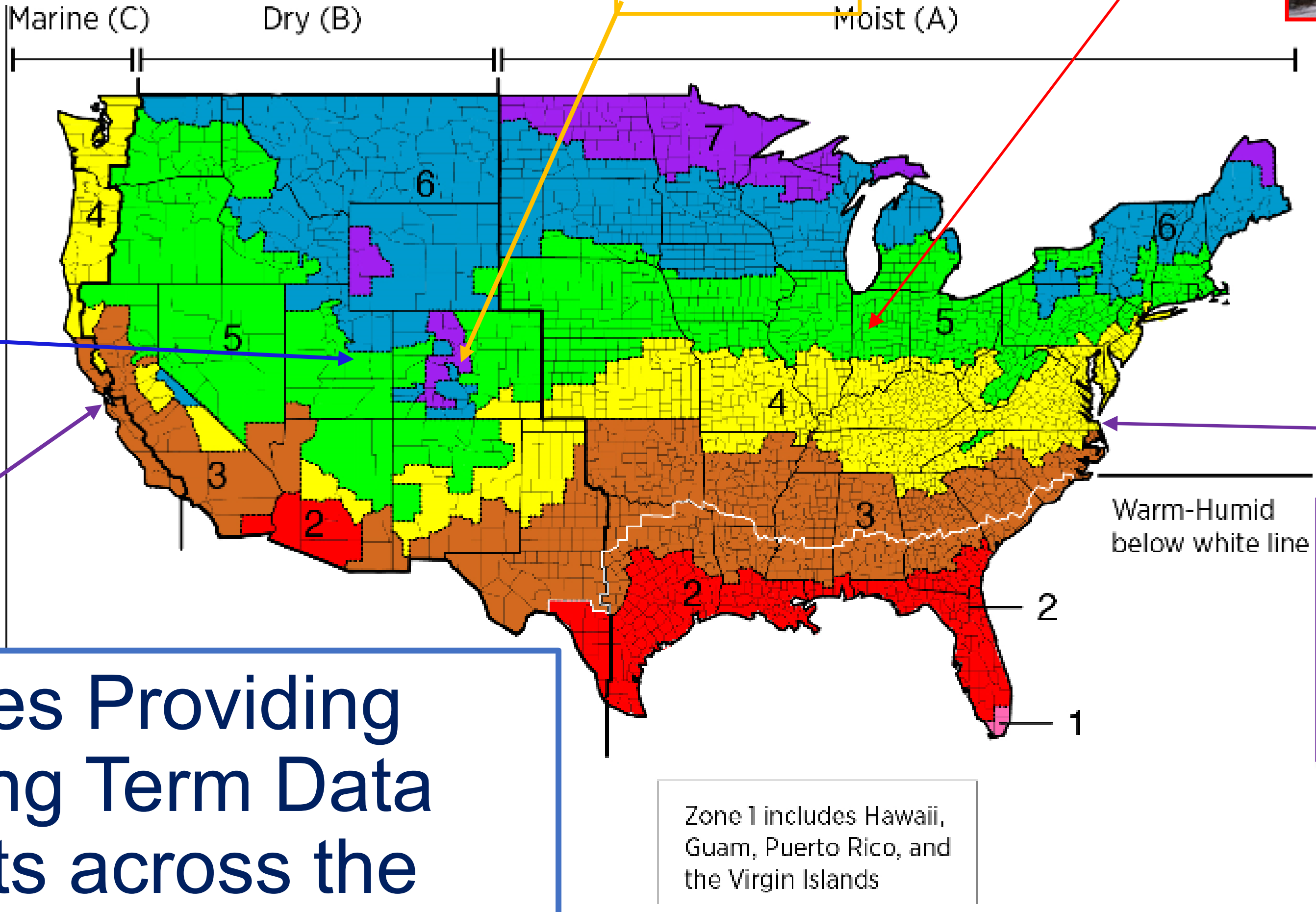
Sites Providing Long Term Data Sets across the IECC Climate Zones

Wendell and Gaffney AK-8

Redfield CO– 5B

Indianapolis Duplex, 5A

Sun Devil Manor UT - 5B



VA Site A – 4A

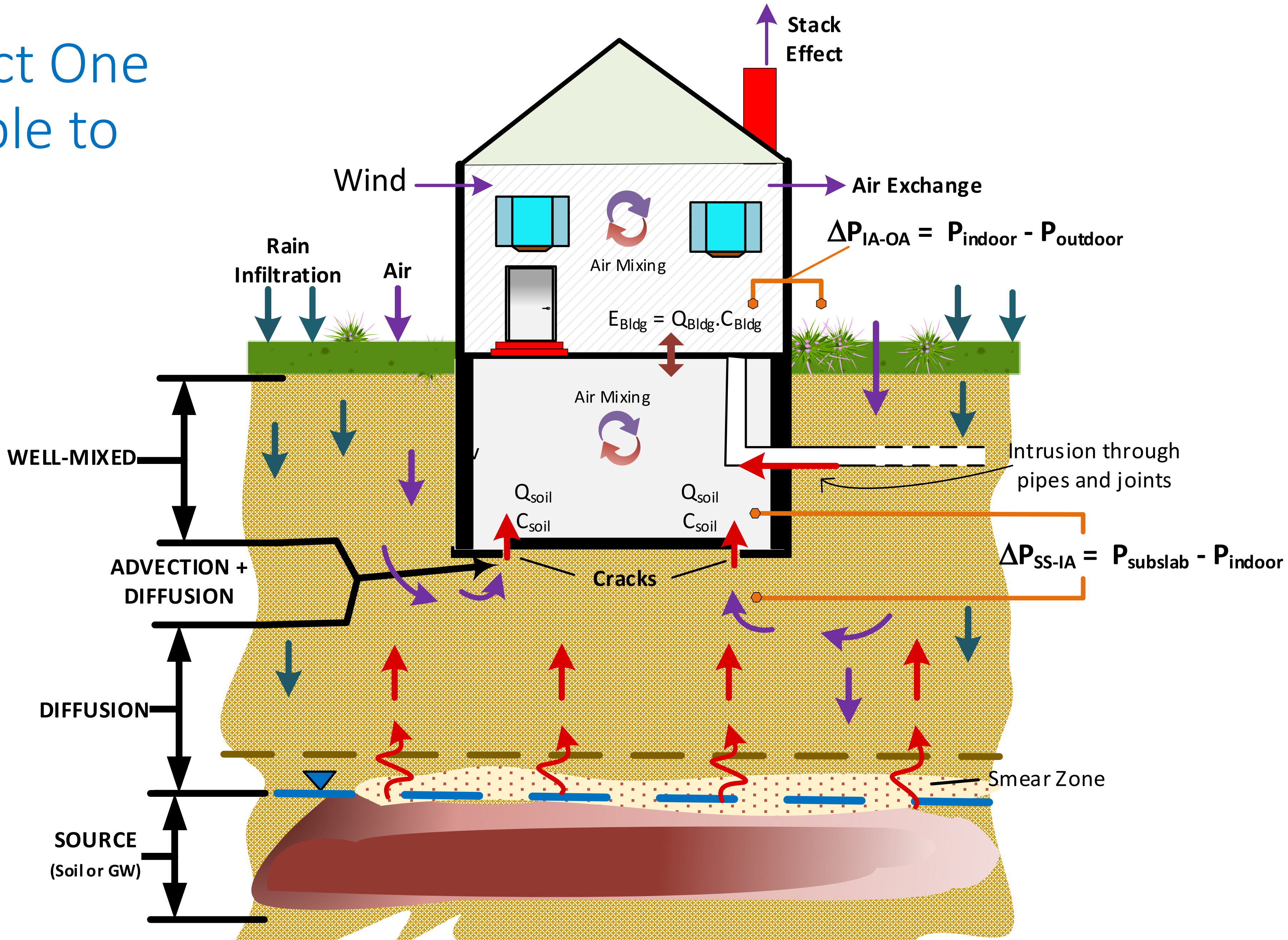
MEW CA – 3C

IECC zones Reprinted form https://basc.pnnl.gov/images/iecc-climate-zone-map

We Shouldn't Expect One Independent Variable to Control Indoor Concentration

"This paper identified about thirteen factors that can affect radon: …soil moisture content, soil permeability, wind, temperature, barometric pressure, rainfall, frozen ground, snow cover, earth tides, atmospheric tides, occupancy factors, season and time of day."

Lewis & Houle, A Living Radon Reference Manual (2009)



Long Term VOC Data Sets:

Sun Devil Manor

Indianapolis (2 floors)

VA Site A (2 zones)

Gaffney

MEW

Simultaneous Indicators and Tracer Data:

VOCs

Radon

Exterior Temperature or Differential Temperature (inside/outside)

Differential Pressure (Subslab vs. indoor or indoor vs. outdoor)

Analysis Tools:

XY Analysis

2:2 Table (Screening)

Graphical Temporal Analysis

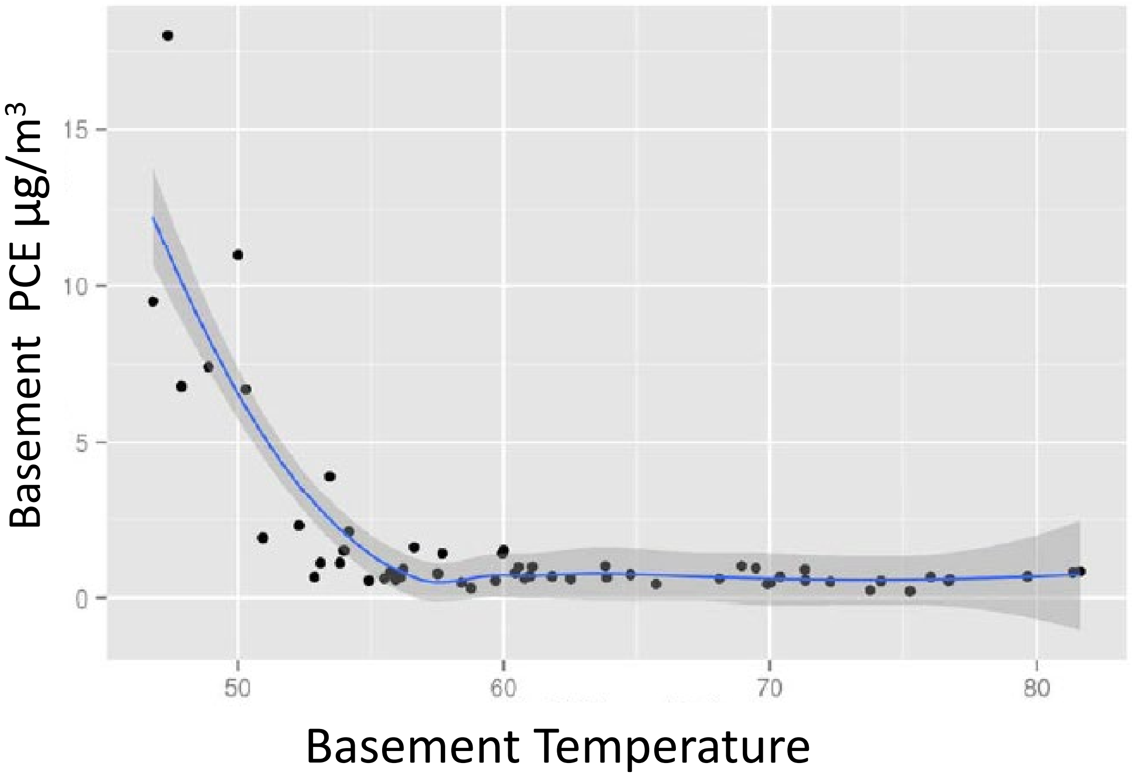
Time Series Analysis

Peak Value Prediction

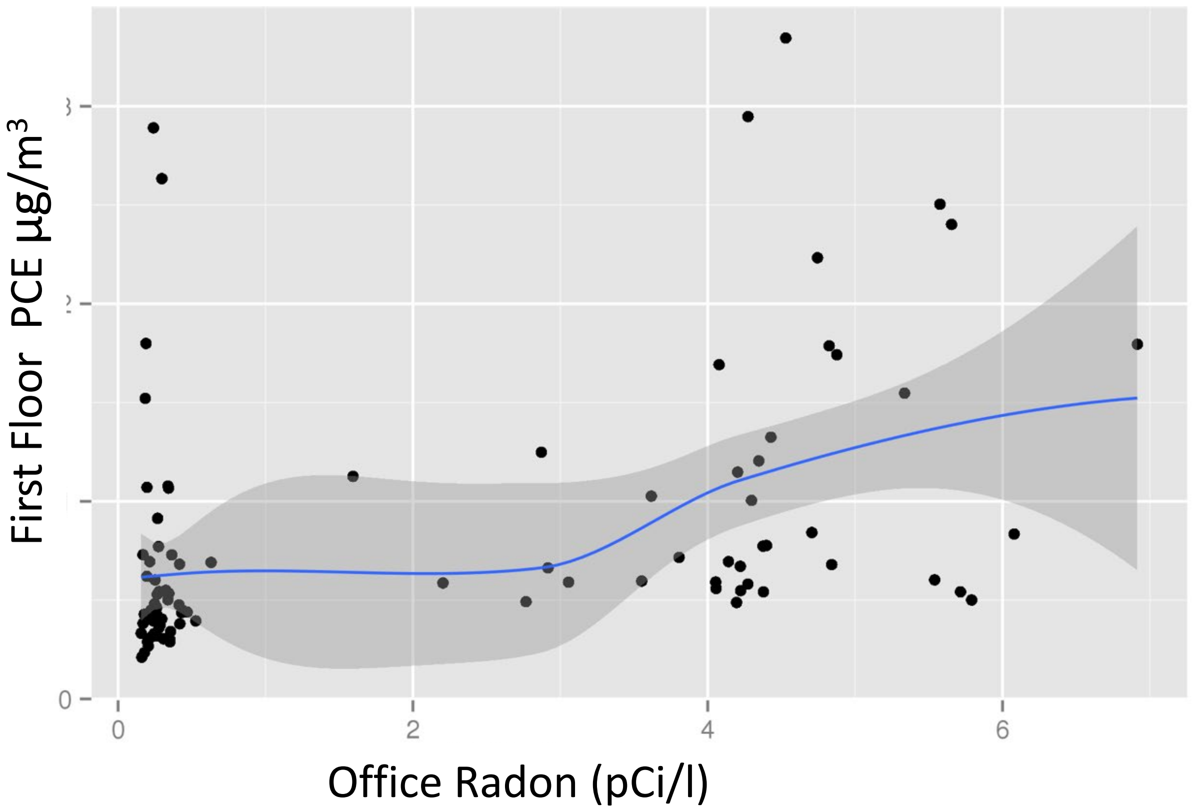
Sampling Strategy Performance

Equivalent Protection ($)

Simple XY Plot Examples – Indianapolis Duplex



PCE vs. Exterior Temperature, Weekly Averages, Basement South: Jan 2011 to Feb 2012

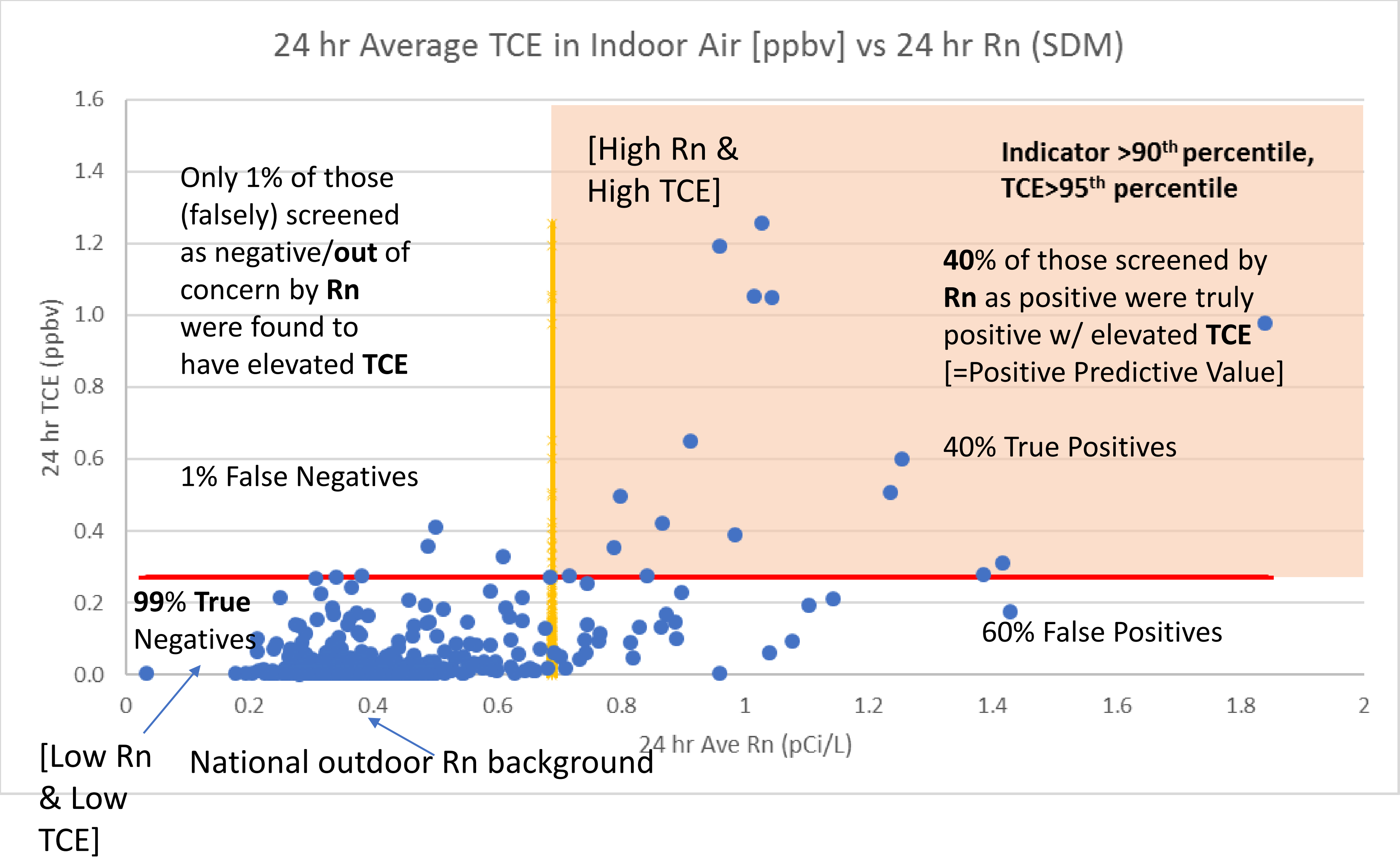


PCE vs. Radon; Daily averages, Upstairs; Dec 14, 2012 to March 8, 2013

Graphs include locally weighted scatterplot smoothing line [blue], with a 95% confidence interval [shaded])

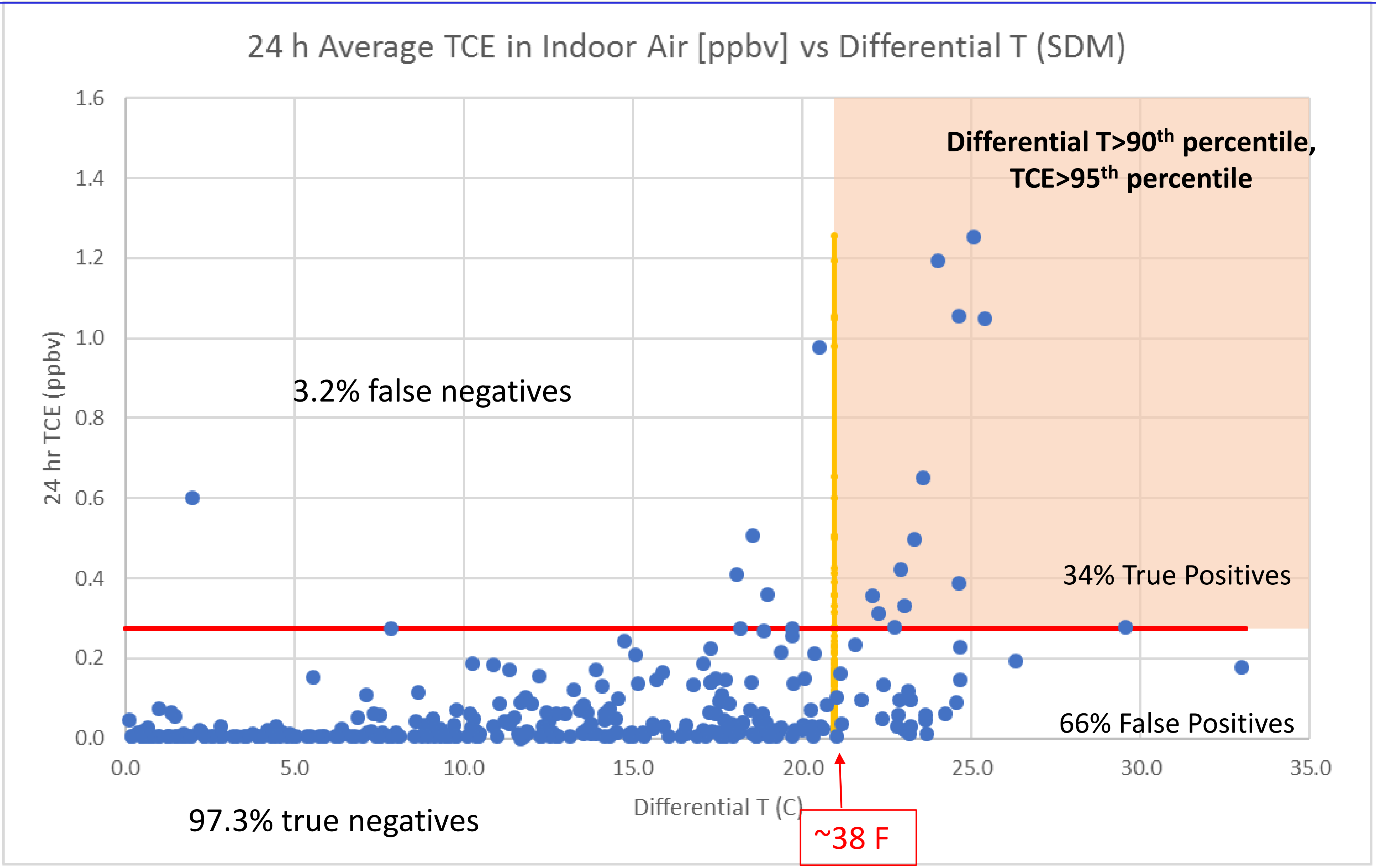
Radon as Indicator of TCE – Sun Devil Manor

Key Point: 40% of the data 'Indicated' by Rn to have higher TCE conc. were found to have higher TCE; 99% of the low radon had low TCE – when not to sample.

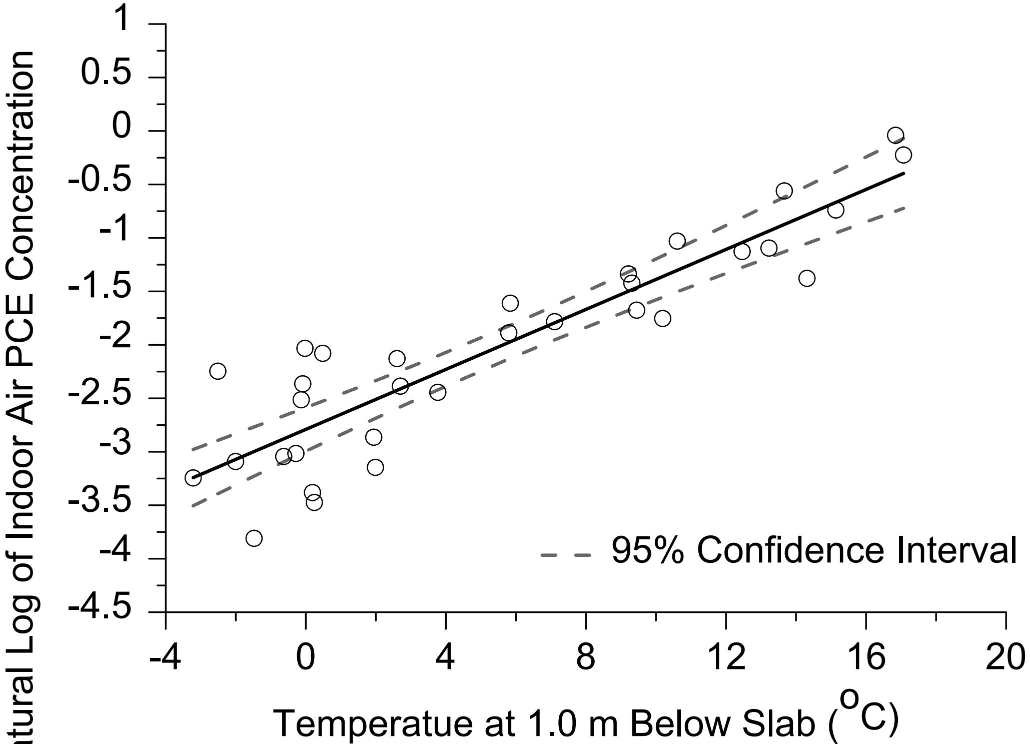


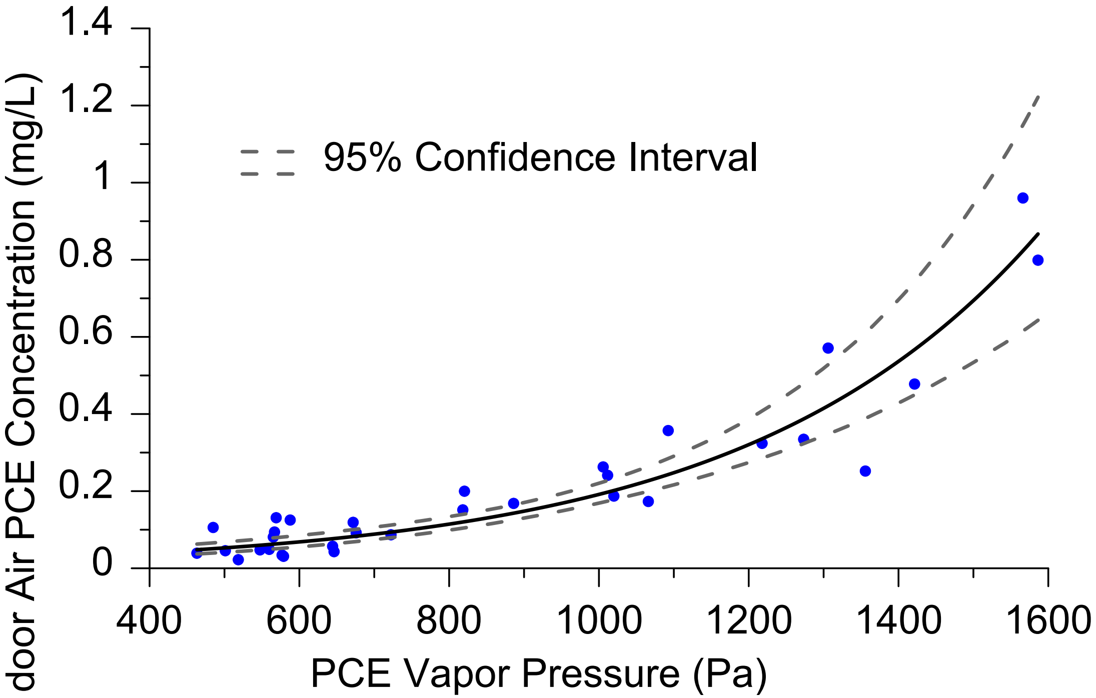
Differential Temperature (Indoor to Outdoor) Indicator (>90th%) – Sun Devil Manor

Key Point: 34% of the samples with Δ temperature above the 90th percentile were above the 95th percentile TCE.



A Plot Twist – Correlation with Rising Soil Temperature in Barnes Study





Barnes, David L., and Mary F. McRae. "The predictable influence of soil temperature and barometric pressure changes on vapor intrusion." *Atmospheric Environment* 150 (2017): 15-23.

Another Example of Winter Not Necessarily Highest (VA site B)

Table 4. Average Indoor Concentrations of TCE from 24-hr Samples at Each Location for Each Sampling Period

Dates	Shed 3 Midway L1 (ppb)		Shed 3 Front Office L2 (ppb)		Shed 6 Lunch Room L3 (ppb)		Shed 6 Big Room L4 (ppb)	
	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
March 2017	24.9	18.9	9.1	6.1	4.3	3.7	2.3	1.5
May 2017	49.5	40.7	21.3	18.0	13.7	24.2	8.2	9.7
Aug 2017	15.3	8.5	8.2	5.5	4.3	4.6	2.4	2.3
Jan 2018	16.7	11.5	6.7	5.7	10.5	14.4	1.7	1.4
May 2018	11.6	4.7	4.9	3.2	3.1	2.1	1.8	1.4
August 2018	20.3	9.8	9.4	3.4	5.4	4.3	3.4	2.0
Grand Total	22.8	22.6	10.0	10.0	6.8	12.1	3.3	4.8

Data from approximately 14 sequential one day Summa canister indoor air samples at each location in each month.

From: Rossner et. all. Demonstration of a Long-Term Sampling and Novel Analysis Approach for Distinguishing Sources of Volatile Organic Compounds in Indoor Air , 2020 https://www.serdp-estcp.org/content/download/51955/511220/file/ER-201504%20Final%20Report.pdf

Long Term VOC Data Sets:

Sun Devil Manor

Indianapolis (2 floors)

VA Site A (2 zones)

Gaffney

MEW

Simultaneous Indicators and Tracer Data:

VOCs

Radon

Exterior Temperature or Differential Temperature (inside/outside)

Differential Pressure (Subslab vs. indoor or indoor vs. outdoor)

Analysis Tools:

XY Analysis

2:2 Table (Screening)

Graphical Temporal Analysis

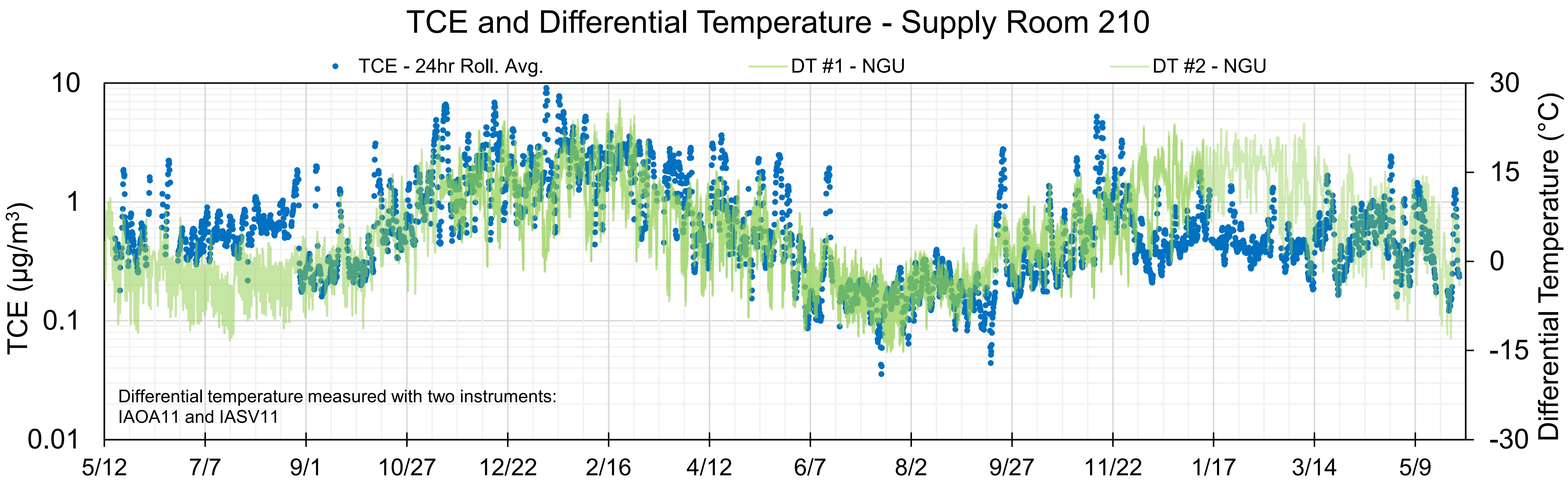
Time Series Analysis

Peak Value Prediction

Sampling Strategy Performance

Equivalent Protection ($)

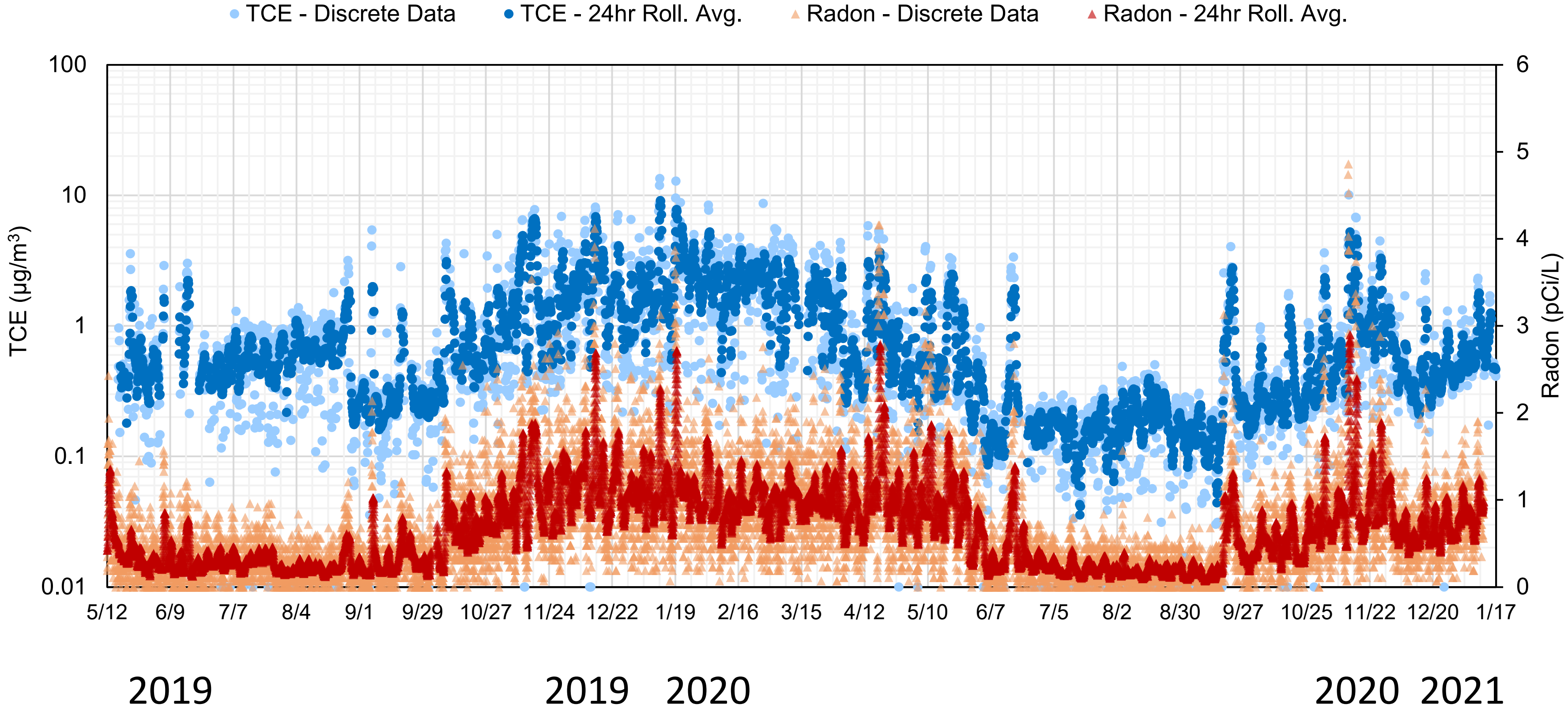
TCE vs. Temperature: Stack Effect Pattern at Supply Room – VA Site A



Key Point: Graph shows an apparent relationship between TCE concentration in indoor air and differential temperature (inside and out). High differential temperature means it is cold outside!

TCE vs. Radon Stack Effect Pattern at Supply Room – VA Site A

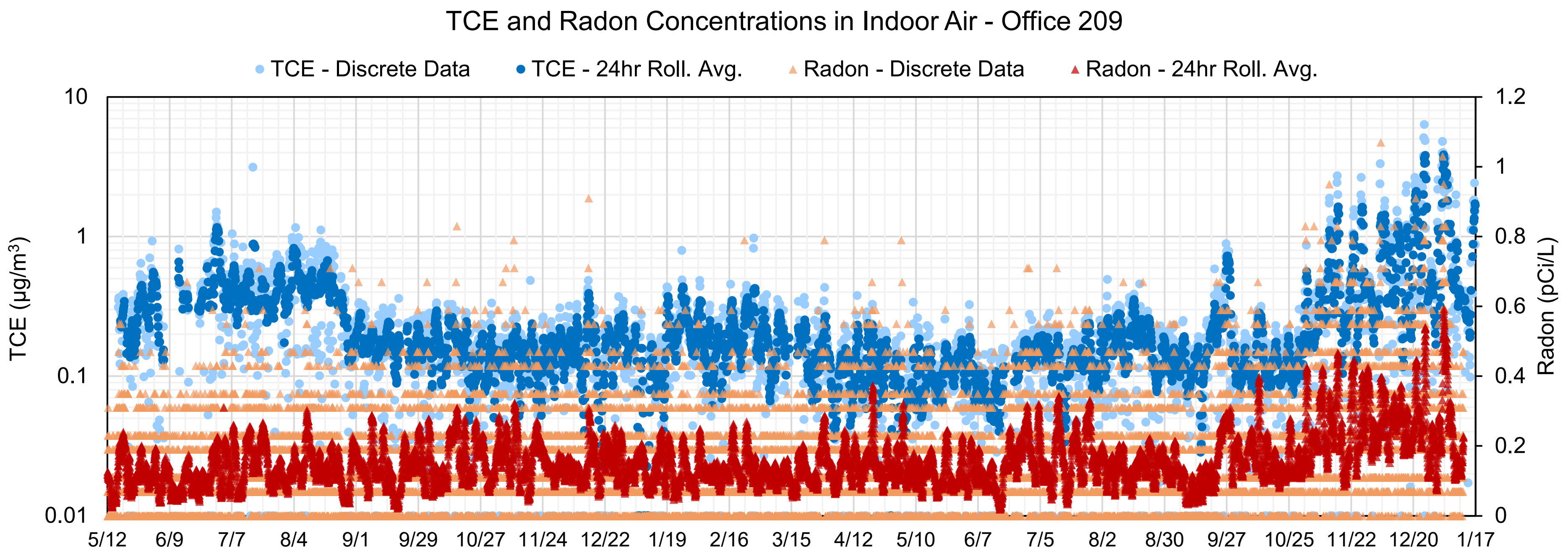
Key Points: Seasonal variation in VI for both pollutants consistent with stack effect pattern at this location. Stack effect more likely in heating season. The stack effect is when warm air moves upward in the building, potentially drawing in soil gas.



TCE Descriptive Statistics

Sample ID	EIA-11
5 %ile	0.09
10 %ile	0.14
25 %ile	0.25
Median	0.47
75 %ile	1.14
90 %ile	2.60
95 %ile	3.63
Maximum	13.4
Average	0.97
StDev	1.27
Coeff. Var.	1.31
% Detected	98%
Count	3,473

Office Zone 3; VA Site A – TCE with Weak Radon Signal



2019 2019 2020 2020 2021

TCE Descriptive Statistics

Sample ID	EIA-10
5 %ile	0.01
10 %ile	0.04
25 %ile	0.10
Median	0.17
75 %ile	0.28
90 %ile	0.49
95 %ile	0.73
Maximum	6.34
Average	0.26
StDev	0.39
Coeff. Var.	1.50
% Detected	93%
Count	3,464

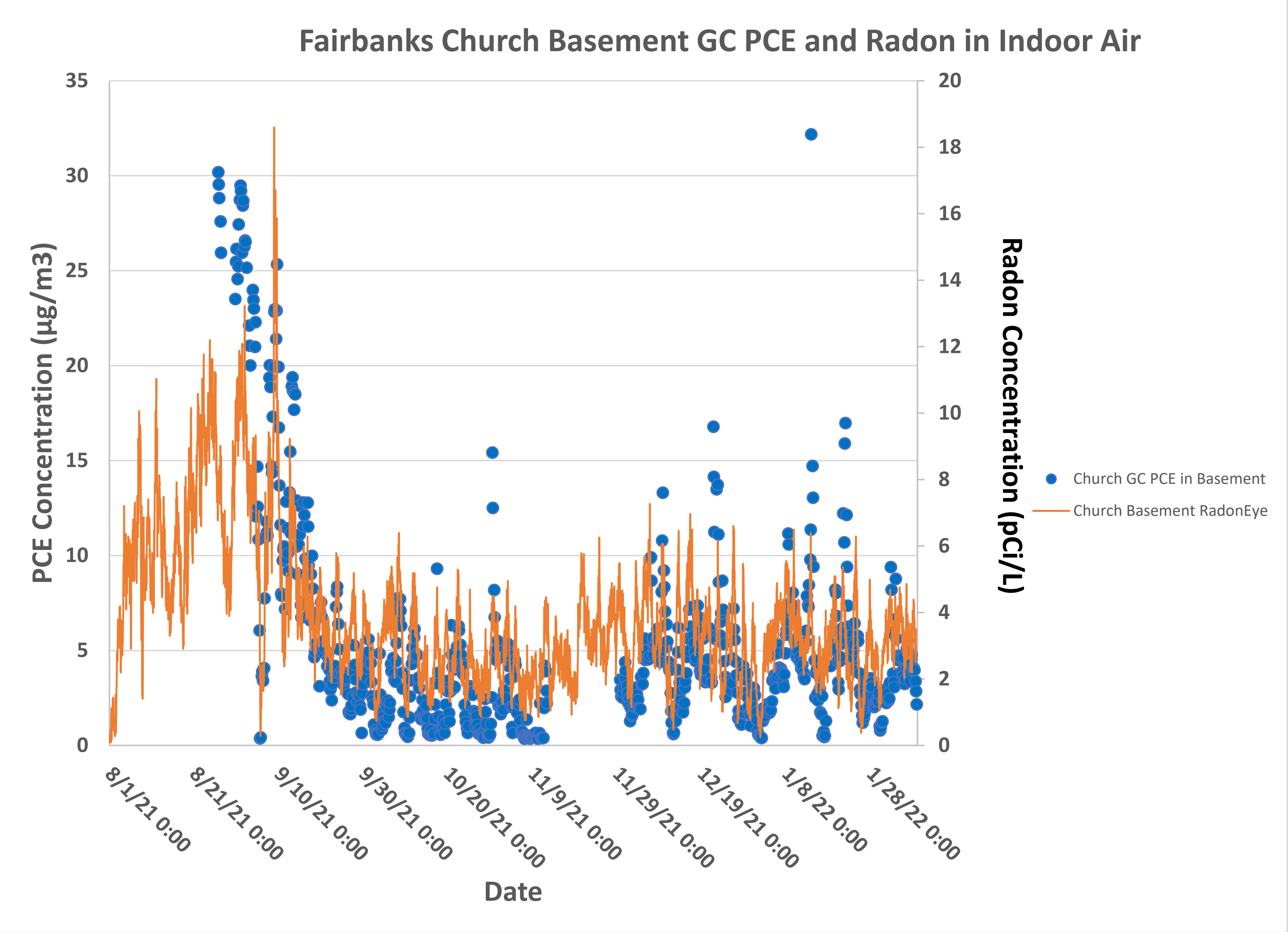
Key points: After more than a year of inactivity (average Sept '19 through Oct '21 = 0.15 µg/m^3 ± 0.10) this location displayed a modest amount of VI (average TCE Nov '20 through Jan '21 = 0.68 µg/m^3 ± 0.8).

Radon signal very weak relative to baseline: TCE subslab concentration is 29,000 and 13,000 ug/m^3 (1500x screening level). Radon in subslab is 300-500 pCi/l (75x EPA action level)

TCE vs. Radon at Gaffney AK New Data

PCE decline in late summer into winter similar to Barnes published data at same site (different building and different year). Suggests soil temperature effect.

Radon correlation to PCE suggests similar entry and ventilation mechanisms.



What is Time Series Analysis?; Why do it?

- "A univariate time series is a sequence of measurements of the same variable collected over time....at regular time intervals." https://online.stat.psu.edu/stat510/lesson/1/1.1
- The data points in the series aren't independent of each other. Analyzing time series with methods that assume the points are independent i.e. ordinary linear regression, can lead to errors.
- Analysis must take into account the time order of the data points.
- Time series can have trend and seasonality (or other cyclic recurring trends).
- Variations in one time series can explain the variation in a second time series.
- Special statistical methods are needed to correctly analyze time series –i.e. transformations to achieve "stationarity". For example, Autoregressive Moving Average Models (ARMA)

From Chatfield "The Analysis of Time Series An Introduction 6th Edition" and Brockwell & Davis "Introduction to Time Series and Forecasting" 2nd Edition

Key Findings from Indianapolis Time Series Analysis

- A strong statistical relationship shown between increases in radon concentration and VOC concentrations indoors. In some data sets, radon as a predictor was statistically significant at the 99% level and to predict 40 to 60% of the variability in indoor air VOC concentrations.

- The radon literature says as many as 10 variables continuously interact to control indoor radon concentrations. We found that the proportion of the VOC variability predicted by any one statistically significant predictor variables alone was modest (<30%).

- The week-to-week change in the differential temperature (and thus the stack effect) was more important than the absolute value of the differential temperature. Indoor air concentrations of VOCs are expected to be high when the weather is suddenly getting colder but would not necessarily be expected to be as high during a period of sustained cold weather.

EPA/600/R-15/070 | October 2015 | https://clu-in.org/download/issues/vi/VI-EPA-600-R-15-070.pdf

Key Findings from Time Series and Machine Learning Analysis of VA Site A Supply Room

- The most significant terms ($p<0.01$) in the time series analysis of current TCE concentration were previous TCE concentration, current radon concentration, radon 6 hours before the higher VOC event, current barometric pressure, and a term describing the regularly recurring behavior of TCE over diurnal cycles.
- When several regression and machine learning methods were applied to the same data, they agreed that radon was the best predictive variable for TCE, with barometric pressure second best. Radon often far outperformed other variables.
- Decreasing barometric pressure over the last day was associated with increasing TCE.
- Strongly increasing or decreasing wind speeds over the last day were both associated with increasing TCE. Increasing outdoor wind speeds between approximately 5 and 20 mph were correlated with higher indoor air TCE.
- The descriptive statistical methods associated radon, TCE, and differential temperature, which fits a classical stack effect-controlled model of VI. Both the time series and machine learning ranked barometric pressure as a more important influence on VI than temperature. One possible explanation is radon provided at least the same “information content” that differential temperature would have, if radon information was not available. The analysis however shows that radon provided better “information content” than differential temperature alone at this location.

Temporal Variability in an Industrial Building –Time Series and Machine Learning Analysis; Groundwater Monitoring and Remediation
https://ngwa.onlinelibrary.wiley.com/doi/10.1111/gwmr.12453 Spring 2021 p 87-98

Long Term VOC Data Sets:

Sun Devil Manor

Indianapolis (2 floors)

VA Site A (2 zones)

Gaffney

MEW

Simultaneous Indicators and Tracer Data:

VOCs

Radon

Exterior Temperature or Differential Temperature (inside/outside)

Differential Pressure (Subslab vs. indoor or indoor vs. outdoor)

Analysis Tools:

XY Analysis

2:2 Table (Screening)

Graphical Temporal Analysis

Time Series Analysis

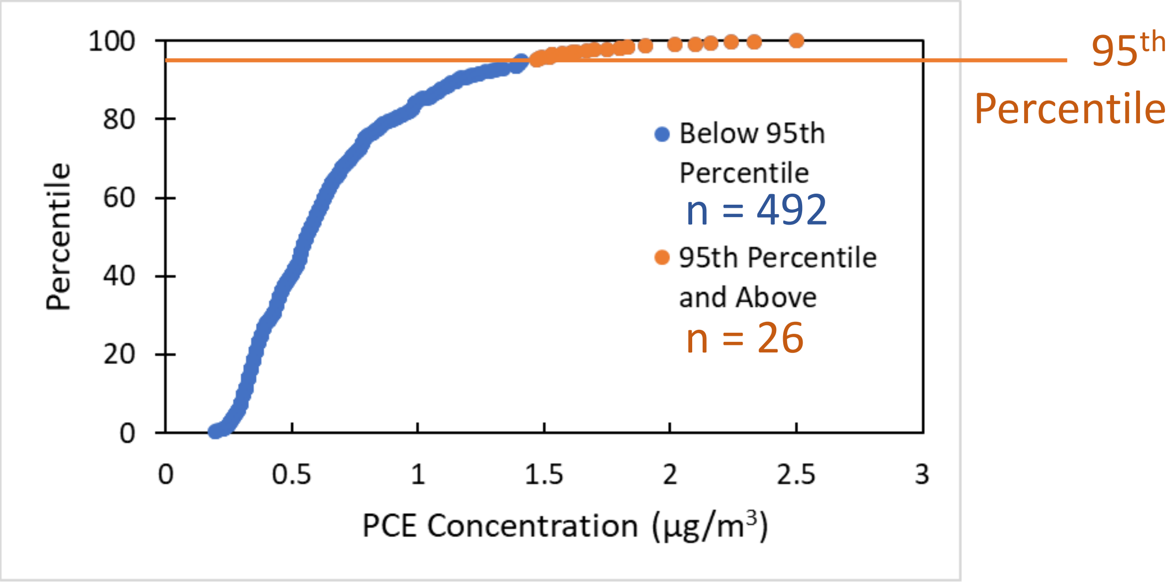
Peak Value Prediction

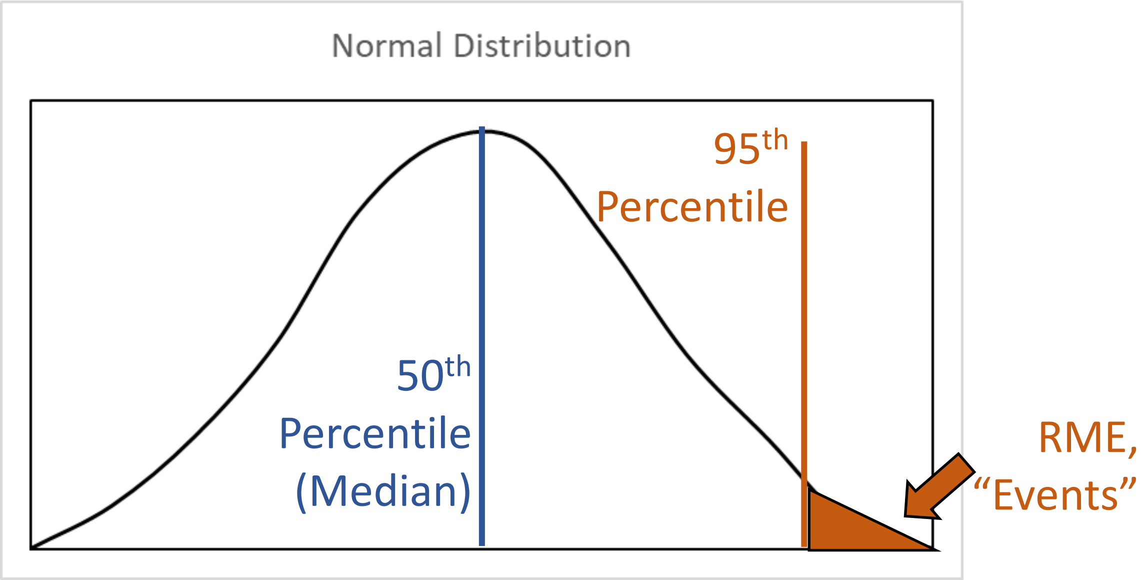
Sampling Strategy Performance

Equivalent Protection ($)

Understanding temporal variability of ITS

- We ranked concentrations of chlorinated compounds by their indoor concentration percentiles
- We chose to analyze 95th percentile and above events to represent the reasonable maximum exposure (RME)
- 5% of all the observations will be at or above the 95th percentile level.
- We classify all RME values as "Events"





Understanding temporal variability of ITS

Date	Time	PCE Concentration (µg/m^3)	PCE Percentile	Days Before Event	Hours Before Event
12/10/2011	7:00	0.25	44.4	1	12
12/10/2011	10:00	0.34	71.9	1	9
12/10/2011	13:00	0.34	85.8	1	6
12/10/2011	16:00	0.36	90.4	1	3
12/10/2011	19:00	0.32	95.9	0	0
12/10/2011	22:00	0.51	93.4	1	15+
12/11/2011	1:00	0.66	85.8	1	15+
12/11/2011	4:00	0.44	55.5	1	12
12/11/2011	7:00	0.44	46.2	1	9
12/11/2011	10:00	0.38	46.2	1	6
12/11/2011	13:00	0.63	67.6	1	3
12/11/2011	16:00	0.98	99.0	0	0
12/11/2011	19:00	1.09	98.8	0	0
12/11/2011	22:00	1.13	98.2	0	0
12/12/2011	1:00	1.61	98.6	0	0

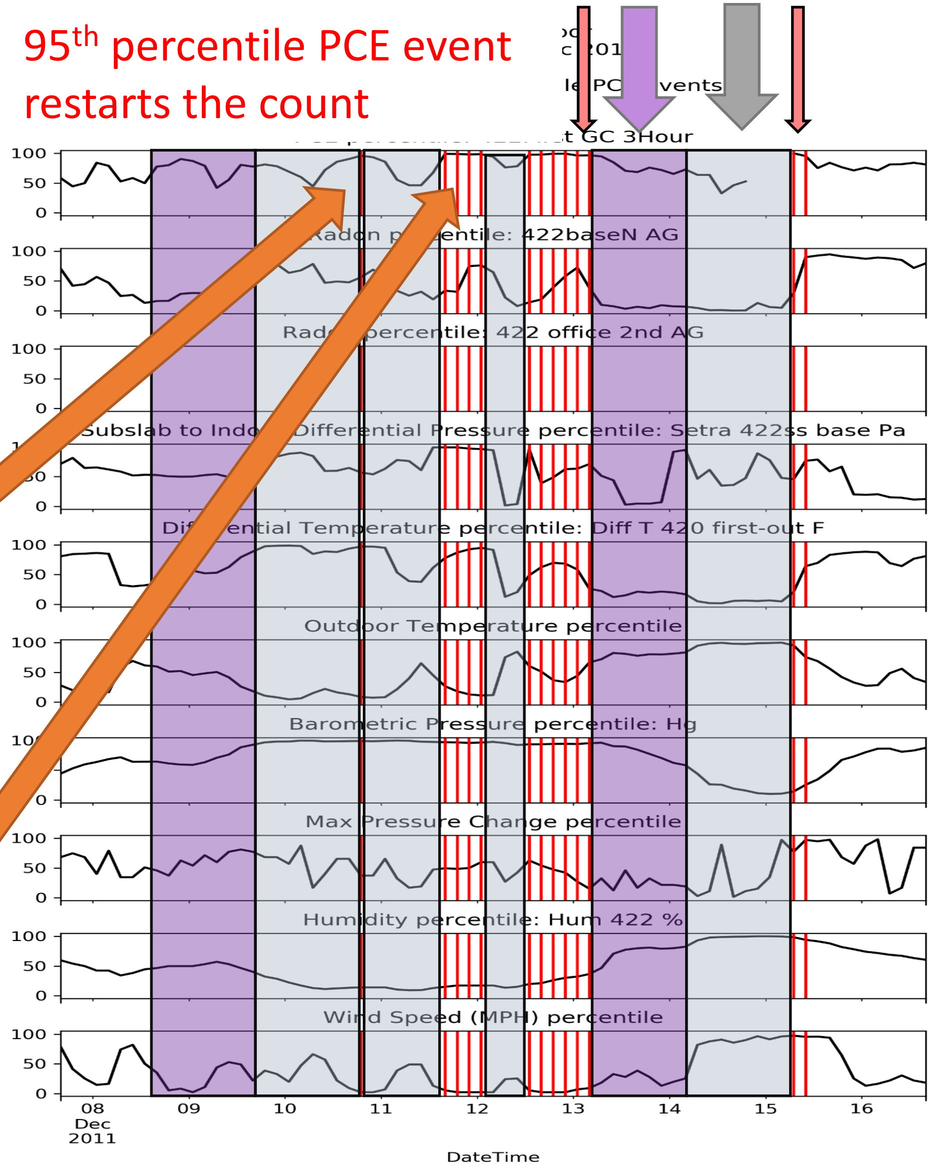
VOC concentrations in indoor air greater than the 95th percentile of the overall data set may have occured on a one-time basis or in a set of consecutive data points

Event, count is restarted

Multiple Events in a row

95th percentile PCE event restarts the count

95th percentile PCE event
1 Day Before Event
2 Days Before Event



Peak Value Analysis Paper Conclusions

- Data analysis discussed the 15 hours and 4 days prior to the event.
- Relative to site-specific baseline values, the results show that cold or falling outdoor temperatures, rising cross slab differential pressure, and increasing indoor radon concentrations can predict upcoming peak VOC concentrations. However, cold outdoor air temperature was not useful at one site where elevated shallow soil temperature was a better predictor.
- Correlations of peak VOC concentrations to elevated or rising barometric pressure and low wind speed were also observed, with exceptions.
- This study shows how the independent variables that control peak indoor air VOC concentrations are specific to building types, climates, and VI conceptual site models.

Observation of Conditions Preceding Peak Indoor Air Volatile Organic Compound Concentrations in Vapor Intrusion Studies; Groundwater Monitoring and Remediation 2021
https://ngwa.onlinelibrary.wiley.com/doi/10.1111/gwmr.12452, Spring 2021, p 99-111.

Long Term VOC Data Sets:

Sun Devil Manor

Indianapolis (2 floors)

VA Site A (2 zones)

Gaffney

MEW

Simultaneous Indicators and Tracer Data:

VOCs

Radon

Exterior Temperature or Differential Temperature (inside/outside)

Differential Pressure (Subslab vs. indoor or indoor vs. outdoor)

Analysis Tools:

XY Analysis

2:2 Table (Screening)

Graphical Temporal Analysis

Time Series Analysis

Peak Value Prediction

Sampling Strategy Performance

Equivalent Protection ($)

Sampling Performance Analysis Approach: Did I&T Increase the odds of seeing upper end concentration?

Or

Or

> ?

VISL or Mean or 95th % or 50% of total exposure

Long Term Indoor Concentration Data Sets ≈real concentration distribution ≈ Approximation of Reality

Apply Sample Scheduling Approach

Test many 2 or 4 possible sample sampling events

Compare Subsample Mean or Max To

Goal= VI Screening Level, True Distribution Mean or Percentile

Evaluate Whether Confident and Accurate Enough

Metric, Probability or Odds

Data Sets Tested in This Study (n is # for VOCs)

- Sun Devil Manor (Residential); unoccupied, with land drain open, without blower door, n=342 daily averages
- Indianapolis Duplex (Residential) – unoccupied, data from two floors; without mitigation; n=58 weeklong samples or 49 weeklong with high time resolution radon ; n=136 daily averages
- Moffett Field Building 15 (Commercial) – normal operating conditions; n =156 daily averages
- Gaffney Alaska (Commercial) – normal operating conditions, n= 27 days of sampling
- Virginia Site A (Industrial) – two locations – normal operating conditions n=589 daily averages

Sample Scheduling Approaches Tested in this Study

- One sample per calendar season (Winter = Dec 1 to Feb 28, Spring March 1 to May 31…..) – either winter/summer or four quarterly samples

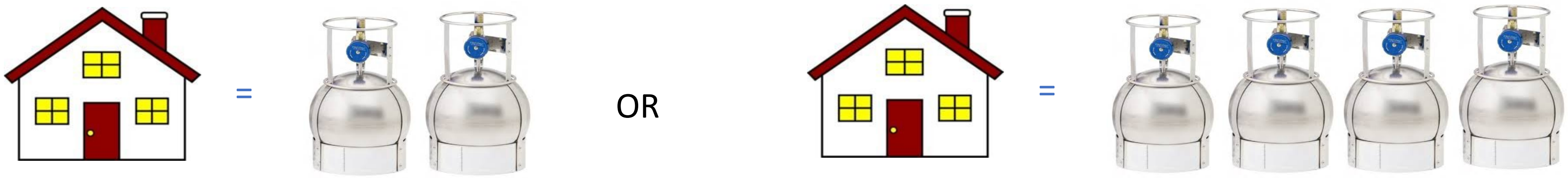
- Half the samples in heating season (November 1 to March 31st), half not in heating season
- All samples in heating season.
- OR sampling event begun based on:
  - a decrease in temperature day over day of 5 F (in either daily low or daily average)
  - indoor/outdoor differential temperature of 15 F
  - a negative differential pressure of 0.01 inches of water or 2.49 Pa or more negative
  - a day over day increase in radon concentration of 0.5 pCi/l
  - a threshold Level of > 2 pCI/l in radon
  - exceeding the 90th percentile of radon levels expected for the structure either based on the first month of sampling or the full data set.

Goals for a Sampling Strategy

- Is a >95% confidence in making the assessment decision about an individual structure required? (<5% false negative?)
- Sampling strategies should be applicable to a wide variety of buildings, using a minimum of easily available preexisting information.
- Sampling strategies should be robust – perform well across a variety of situations.

Sampling Performance Analysis Assumptions

Key Question: Will the proposed strategies help achieve better odds of observing upper end concentrations than random sampling?



- Most Scheduling Approaches Tested with 2 vs. 4 Sampling events
- Assumed computer or person would “evaluate” previous data at midnight to decide whether to sample that day (starting in theory at 12:01 AM).
- Evaluation could be automated/triggered sampling; human in the decision loop, weather forecast, or calendar based.
- All allowable combinations of sampling days based on scheduling approach considered equally likely.
- Days to be sampled will be defined as 24-hour block averages because that is the most common sampling technique in the field overall and how even continuous data is often evaluated. This was then either one Summa sample or a daily average GC result.

Metrics, Probabilities, Tested

- At least one sample of the two or four samples collected will equal or exceed the “true” mean concentration
- AAt least one of the two or four samples taken will be equal to or exceed the 95% UCL on the mean of the VOC distribution
- At least one of the two or four samples will exceed the 95th percentile of the underlying distribution
- At least one of the two or four samples taken will come from above the 50% of total cumulative exposure point.

Percentage Chance with Four Samples That At Least One Exceeds 90th Percentile of VOC Distribution – Effect of Radon Guidance

Site/Averaging Duration	Radon below 50th percentile of full radon dataset	Radon below average of full radon dataset	Random	Radon greater than 90th percentile of full radon dataset
Sun Devil Manor Daily	13.6	13.3	34.8	94.7
Sun Devil Manor Weekly	27.0	19.2	36.4	100.0
Indy Base N Week	17.4	19.0	38.7	0.0
Indy Base S Day	25.5	24.3	35.6	47.6
Indy Base S Week	28.9	32.4	35.9	0.0
Indy First Floor Daily	6.3	0.0	35.6	57.9
Indy First Floor Weekly	15.4	16.0	35.9	80.0
VA Site A Daily Womens BR	39.2	39.1	34.5	17.9
VA Site A Weekly Womens BR	32.2	44.6	35.9	0.0
VA Site A Daily Supply Room	1.4	2.6	34.5	76.4
VA Site A Weekly Supply Room	9.5	8.9	35.9	95.5
VA Site A Daily Location 08	40.0	37.4	34.6	67.3
All Data Sets Average	*21.4*	*21.4*	*35.7*	*53.1*

Percentage Chance with Four Samples That At Least One Exceeds 95th Percentile of VOC Distribution – Effect of Radon Guidance

Site/Averaging Duration	Radon below 50th percentile of full radon dataset	Radon below average of full radon dataset	Random	Radon greater than 90th percentile of full radon dataset
Sun Devil Manor Daily	4.0	3.1	19.1	77.6
Sun Devil Manor Weekly	0.0	0.0	19.7	80.0
Indy Base N Week	17.4	19.0	24.9	0.0
Indy Base S Day	5.6	0.0	19.2	47.6
Indy Base S Week	28.9	32.4	23.0	0.0
Indy First Floor Daily	0.0	0.0	19.2	23.5
Indy First Floor Weekly	0.0	0.0	23.0	80.0
VA Site A Daily Womens BR	18.1	19.9	18.9	9.3
VA Site A Weekly Womens BR	0.0	20.2	21.4	0.0
VA Site A Daily Supply Room	0.0	1.3	18.9	62.7
VA Site A Weekly Supply Room	0.0	0.0	21.4	89.4
VA Site A Daily Location 08	29.6	27.5	19.4	0.0
All Data Sets Average	*8.6*	*10.3*	*20.7*	*39.2*

Summary Across Multiple Sites – Sampling Analysis

- Sampling four times in heating season worked well at most sites, but very poorly at Gaffney.
- Sampling once in each of four seasons often performed poorly.
- Sampling with Radon guidance often worked well, but not all sites had radon data to test.
- Sampling approaches performed better at the sites/locations that fit the classical stack effect and winter worst theory.
- VI sampling approaches may need to be tailored to specific climate zones and conceptual site models
- Sampling rules give better reliability in predicting the mean than predicting the upper percentiles of the distribution.
- Seeing the 95th percentiles directly requires many samples even with guidance.

Conclusion After Multiple Methods of Analysis

- When the classic stack effect conditions prevail (as they might often with a groundwater source) then decreasing temperature and increasing radon are useful I&T.
- Exceptions have been observed to the temperature trend in cases where the soil source is very near the building.
- Radon is often the most powerful I&T, but there are times when the radon concentration in the subslab is insufficient to be an effective tracer - when the subslab soil gas VOCs are very strong i.e. >10,000 $\mu g/m^3$ and when the slab is a relatively competent barrier to VI (favorable attenuation factor).

For More Details on Analysis Methods and Results

(Slides and Presentation Videos Free Online; Full Text of Papers Available from Authors Upon Request Christopher.lutes@jacobs.com)

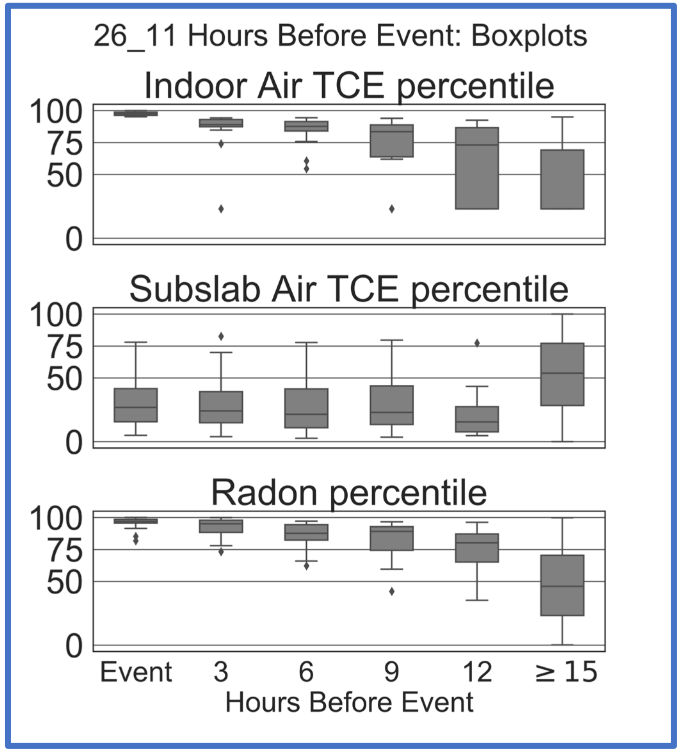
XY Analysis and 2:2 Table (Screening)	*Chlorinated vapor intrusion indicators, tracers, and surrogates (ITS): Supplemental measurements for minimizing the number of chemical indoor air samples—Part 1: Vapor intrusion driving forces and related environmental factors*, Remediation Journal, 2018, Volume 28, Issue 3; p 7-31. 2018 Workshop: https://iavi.rti.org/assets/docs/WorkshopsAndConferences/05_Kurtz_AEHS_03_2018_indicators%20tracers%20and%20surrogates_FINAL.pdf 2017 Workshop: https://iavi.rti.org/assets/docs/WorkshopsAndConferences/05_AEHS_03.2017_Lutesindicators%20tracers%20and%20surrogates%209%20including%20Holton%20and%20Kurtz.pdf
Temporal Trend Analysis	**Sun Devil Manor**: 2014 presentation https://iavi.rti.org/assets/docs/WorkshopsAndConferences/5_JohnsonSunDevil_031814.pdf SERDP Report: https://www.serdp-estcp.org/Program-Areas/Environmental-Restoration/Contaminated-Groundwater/Emerging-Issues/ER-1686/ER-1686 *Temporal variability of indoor air concentrations under natural conditions in a house overlying a dilute chlorinated solvent groundwater plume*. *ES&T Vol* 47 No. 23 (2013): 13347-13354 **Indianapolis**: 2014 Presentation https://iavi.rti.org/assets/docs/WorkshopsAndConferences/4_Lutes_EPAORD_31714.pdf EPA Reports: https://clu-in.org/download/issues/vi/VI-EPA-600-R-15-070.pdf and https://cfpub.epa.gov/si/si_public_file_download.cfm?p_download_id=508271&Lab=NERL **VA Site A**: 2021 Workshop https://iavi.rti.org/assets/docs/04_High%20Res_Indoor_Subslab_2021_AEHS.pdf **Gaffney:** *The predictable influence of soil temperature and barometric pressure changes on vapor intrusion; Atmospheric Environment* 150 (2017): 15-23.
Formal Time Series	**Indianapolis**: EPA Reports: https://clu-in.org/download/issues/vi/VI-EPA-600-R-15-070.pdf and https://clu-in.org/download/issues/vi/vi-epa-600-r-13-241.pdf **VA Site A:** *Temporal Variability in an Industrial Building –Time Series and Machine Learning Analysis*; Groundwater Monitoring and Remediation https://ngwa.onlinelibrary.wiley.com/doi/10.1111/gwmr.12453 Spring 2021 p 87-98
Peak Value Prediction	March 2020 Workshop https://iavi.rti.org/workshops.html *Observation of Conditions Preceding Peak Indoor Air Volatile Organic Compound Concentrations in Vapor Intrusion Studies;* Groundwater Monitoring and Remediation 2021 https://ngwa.onlinelibrary.wiley.com/doi/10.1111/gwmr.12452, Spring 2021, p 99-111.
Sampling Strategy Performance	March 2021 Workshop https://iavi.rti.org/workshops.html https://iavi.rti.org/assets/docs/06_Explanation_of_studies13_2021_AEHS.pdf

Data Sets Analyzed

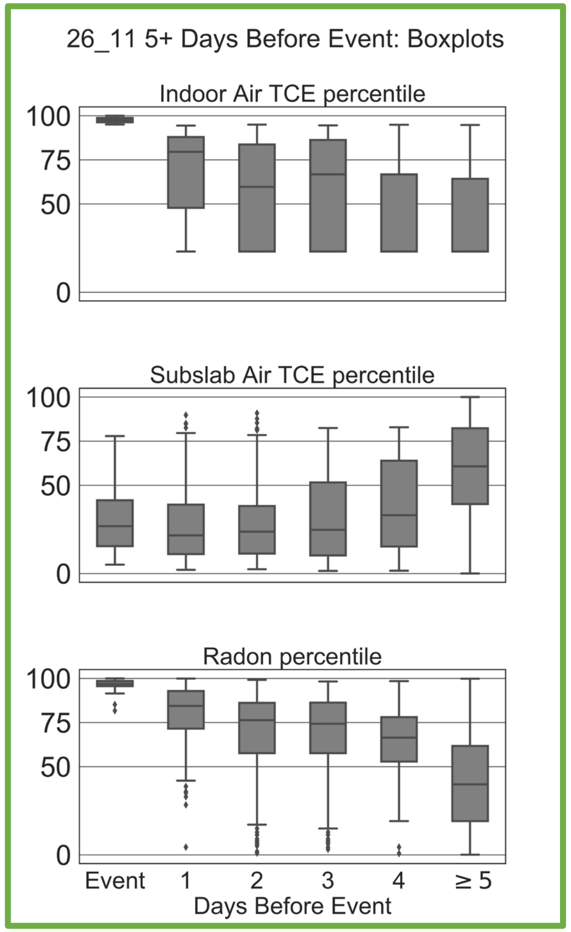
(Sun Devil Manor and VA Site A TCE, and Indianapolis PCE all µg/m^3)

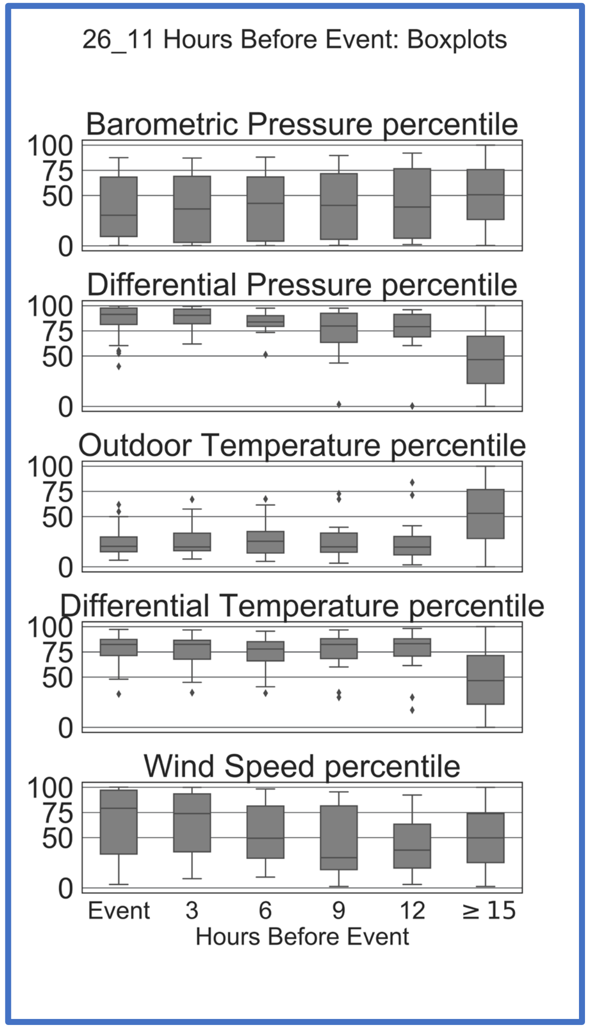
Site/Averaging Duration	Mean	95th UCL on Mean	50th Percentile of Cumulative Total Exposure Curve	95th Percentile of Dataset	Date start	Date end	Number of samples
Sun Devil Manor Daily	0.48	0.58	2.67	1.90	8/15/10	8/21/12	603
Sun Devil Manor Weekly	0.48	0.67	1.27	2.57	8/15/10	8/21/12	95
Indy Base N Week	0.49	0.54	0.53	0.77	3/30/11	2/27/12	45
Indy Base S Day	1.26	1.34	1.29	2.20	8/9/11	2/27/12	136
Indy Base S Week	0.72	0.80	0.75	1.28	3/30/11	2/27/12	49
Indy First Floor Daily	0.61	0.65	0.66	1.08	8/9/11	2/27/12	136
Indy First Floor Weekly	0.36	0.42	0.40	0.77	3/30/11	2/27/12	49
VA Site A Daily Womens BR	0.91	1.08	3.66	4.42	5/17/19	1/10/21	589
VA Site A Weekly Womens BR	0.90	1.15	2.02	3.08	5/17/19	1/10/21	87
VA Site A Daily Supply Room	0.96	1.05	1.71	3.02	5/17/19	1/10/21	589
VA Site A Weekly Supply Room	0.96	1.13	1.62	2.67	5/17/19	1/10/21	87
VA Site A Daily Location 08	1.27	1.46	2.61	5.31	4/19/19	2/3/20	230

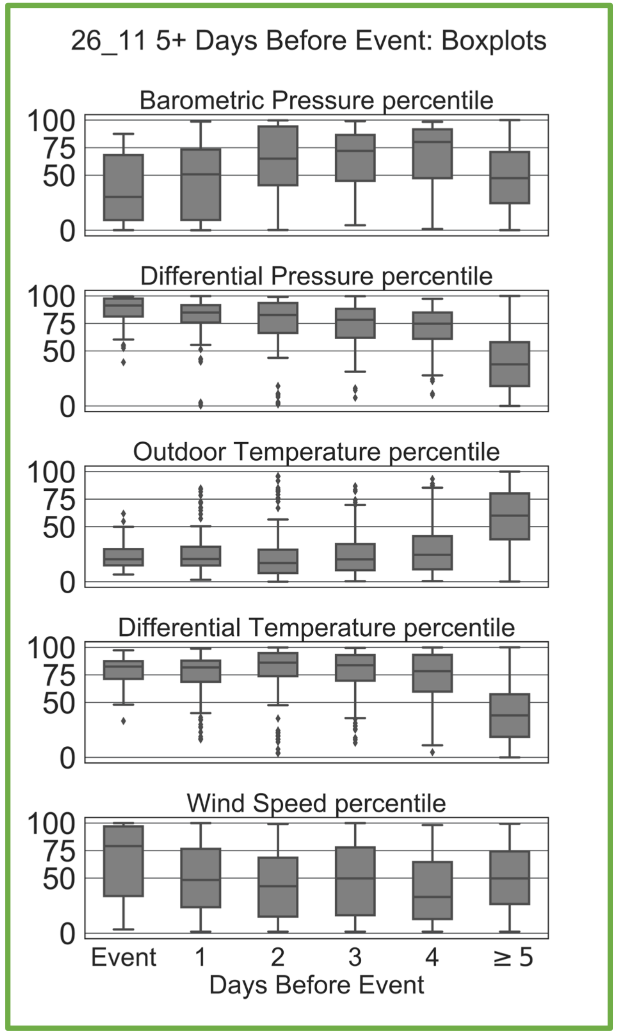
Indicators Preceding >95% TCE Observations: Supply Room (Zone 4)



*Box and whiskers include data from all events within the entire dataset

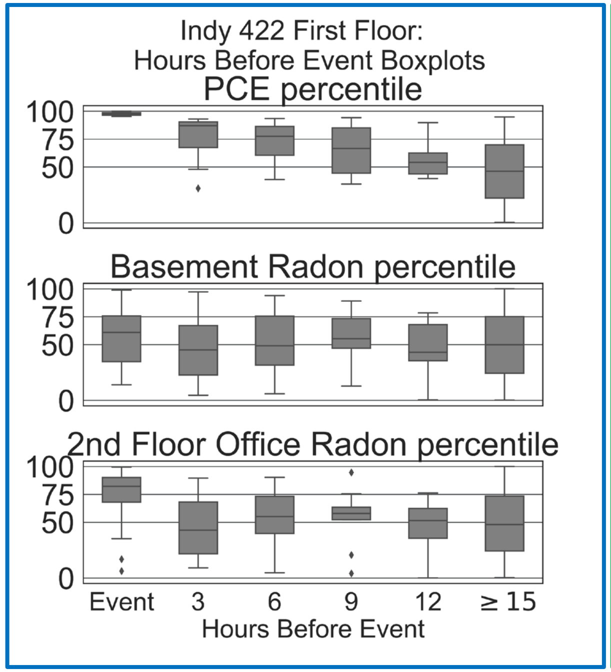


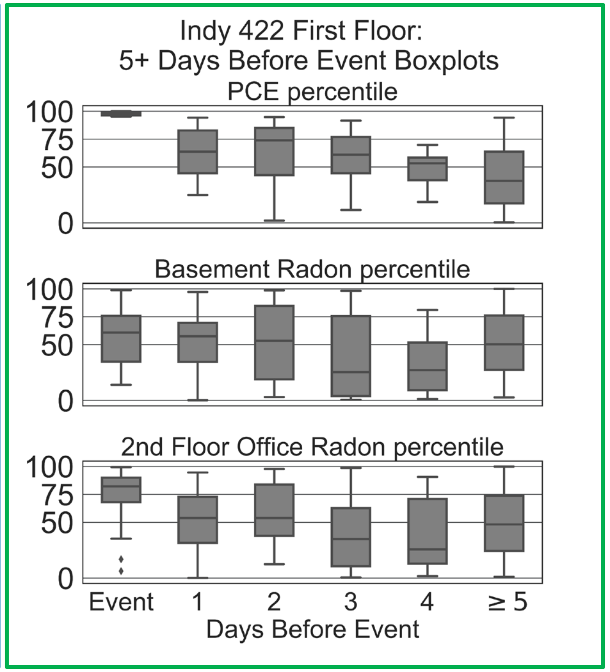


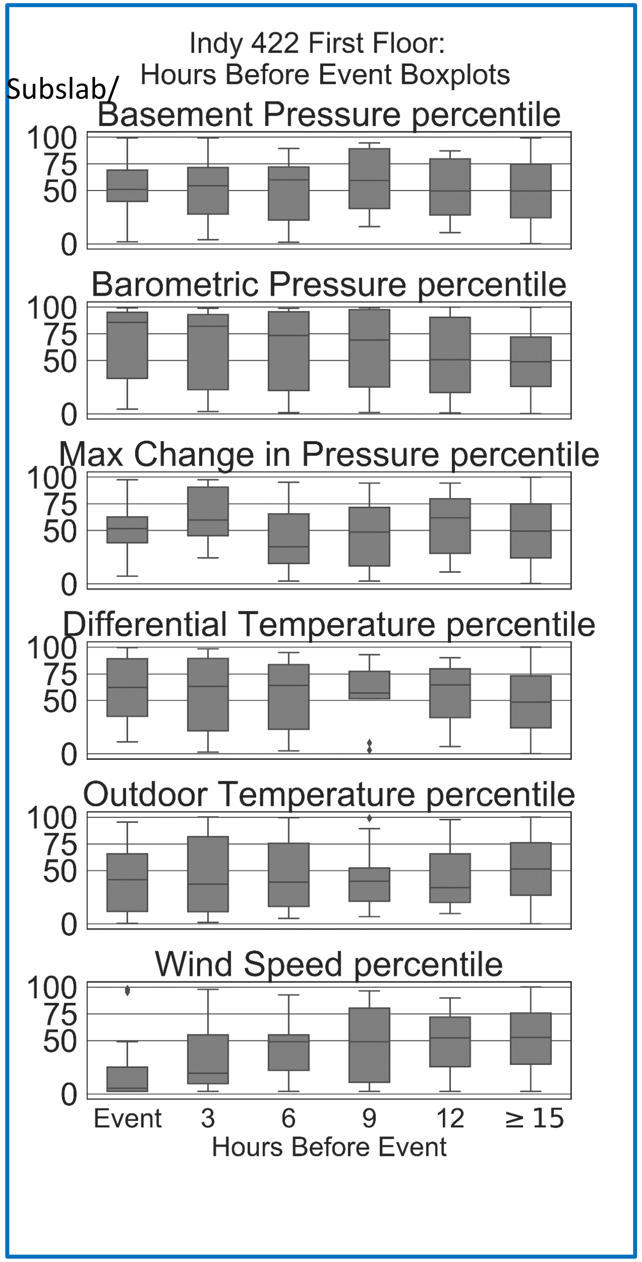


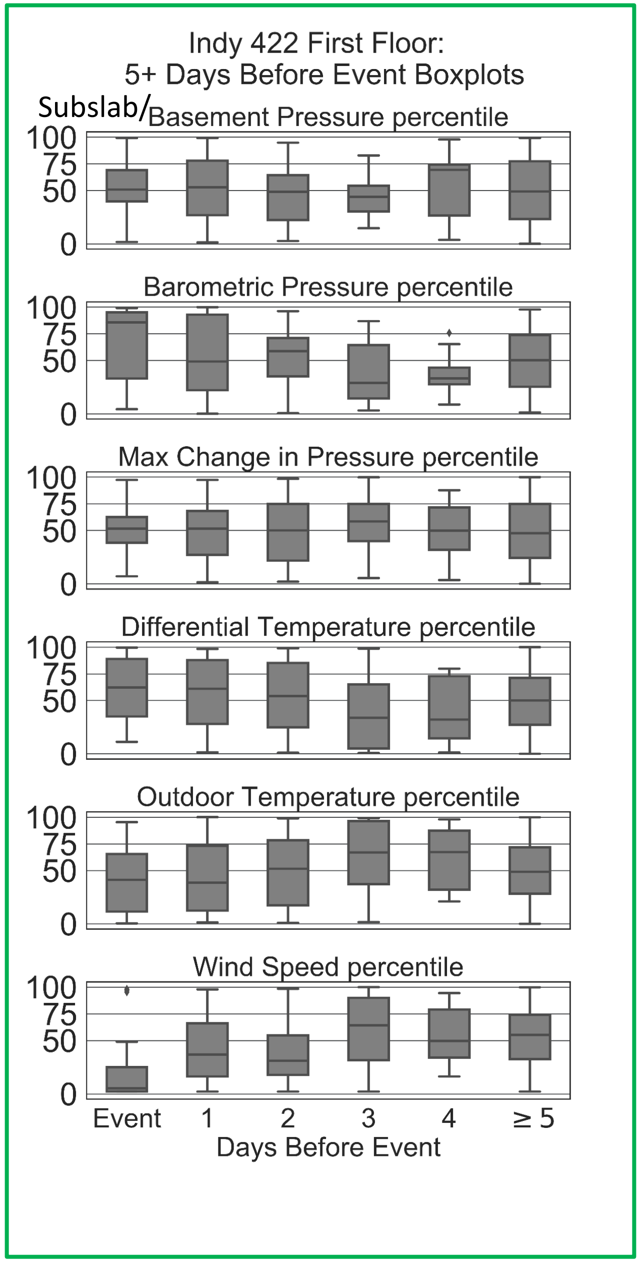
- Increasing and high radon is a good tracer in the supply room
- ΔP is a good indicator
- Cold but not the coldest temperatures associated with high TCE

Indicators Preceding >95% PCE Observations: EPA Indianapolis Duplex First Floor (Heated side)









- 2nd Floor radon right at the event good indicator – soil gas moving upstairs!
- Subslab to basement ΔP not useful
- Increasing barometric pressure somewhat helpful
- Peak PCE associated with decreasing temperatures in the days before and decreasing wind speeds especially in the hours before the event.
- This fits high stack effect, and low AER