EPA Vapor Intrusion Workshop

Why, When, Where, and How You Should Monitor Indoor Radon, Differential Temperature & Pressure During Chlorinated Vapor Intrusion Assessments

Temporal Variability Part 1: New Modes of Analysis and New Building Observations

Chris Lutes, Jacobs and A.J. Kondash, RTI International

EPA Vapor Intrusion Workshop, San Diego CA , *March 17th, 2020*

Agenda for Temporal Section

- New mode of analysis focus on the factors that predict reasonable maximum exposure concentration
- Characteristics of US Distribution of Buildings
- Questions to Think About
- Key physical concepts
- Case Studies
  - Moffett Field, CA (Building 15)
  - VA Site A
  - Multiple commercial buildings: continuous monitoring data patterns for resolving key VI questions
  - Gaffney AK (large building study)
  - EPA Indianapolis duplex (EID)
  - Sun Devil Manor (SDM), Layton, UT

A Key Term Repeated 17 Times in EPA 2015 VI Guide "Reasonable Maximum Exposure"

- EPA 2015 VI guide definition: ***reasonable maximum exposure (RME)***

"A semi-quantitative term, referring to the lower portion of the high end of the exposure distribution; conceptually, above the 90th percentile exposure but less than the 98th percentile exposure."

- *"EPA recommends basing the decision about whether to undertake response action for vapor intrusion ….on a consideration of a reasonable maximum exposure"*
- Today we discuss primarily the exposure concentration, but don't forget that the exposure frequency and exposure duration are also part of RME.
- Observing the reasonable maximum exposure concentration with random sampling is hard! *"An individual sample, collected at a randomly chosen time, may under-estimate or over-estimate average and reasonable maximum exposure conditions…. to different degrees, depending upon the season of sample collection and other factors."*

Frequency **and** Duration are Important in Geysers (and that water vapor is in high concentration)!

Quotes on this slide from OSWER Publication 9200.2-154; *OSWER Technical Guide For Assessing And Mitigating The Vapor Intrusion Pathway From Subsurface Vapor Sources To Indoor Air . Photo reprinted from* https://warnercnr.colostate.edu/cpam/seminar-tourism-protected-areas/past-participants/old-faithful-yellowstone-national-park-usa/

A Key Term: Reasonable Maximum Exposure: Risk Assessment Guidance for Superfund Part A:

6.4.1 QUANTIFYING THE REASONABLE MAXIMUM EXPOSURE

"There are three categories of variables that are used to estimate intake….exposure concentrations…..exposure frequency and duration……averaging time……For Superfund exposure assessments, intake variable values for a given pathway should be selected so that the combination of all intake variables results in an estimate of the reasonable maximum exposure for that pathway….Under this approach, some intake variables may not be at their individual maximum values but when in combination with other variables will result in estimates of the RME.

Exposure concentration. *The concentration term in the intake equation is the arithmetic average of the concentration that is contacted over the exposure period. Although this concentration does not reflect the maximum concentration that could be contacted at any one time, it is regarded as a reasonable estimate of the concentration likely to be contacted over time. This is because in most situations, assuming long-term contact with the maximum concentration is not reasonable. …..Because of the uncertainty associated with any estimate of exposure concentration, the upper confidence limit (i.e., the 95 percent upper confidence limit) on the arithmetic average will be used for this variable."*

Quotes from OSWER 9285.701A; July 1989
Lognormal and Exponential Distribution diagrams reprinted from: http://people.stern.nyu.edu/adamodar/New_Home_Page/StatFile/statdistns.htm

Bimodal distribution diagrams reprinted from: http://mathcenter.oxford.emory.edu/site/math117/shapeCenterAndSpread/

Figure 6A.9: Lognormal distribution

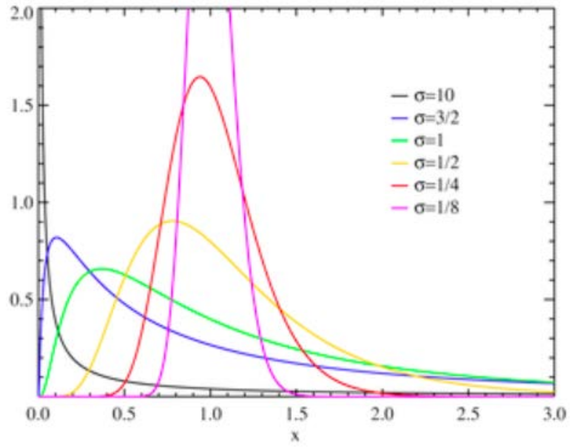
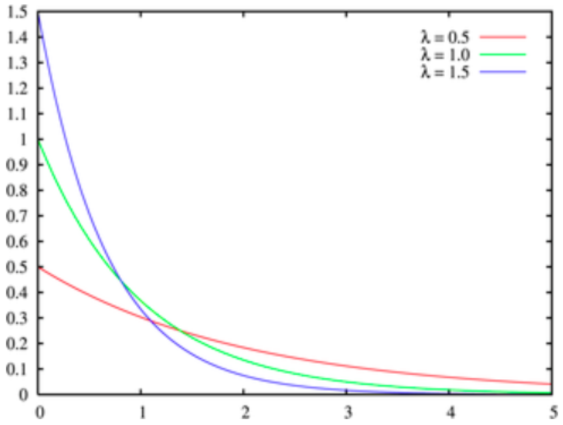
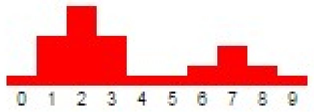
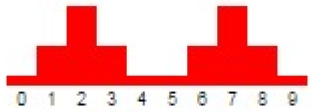


Figure 6A.11: Exponential Distribution





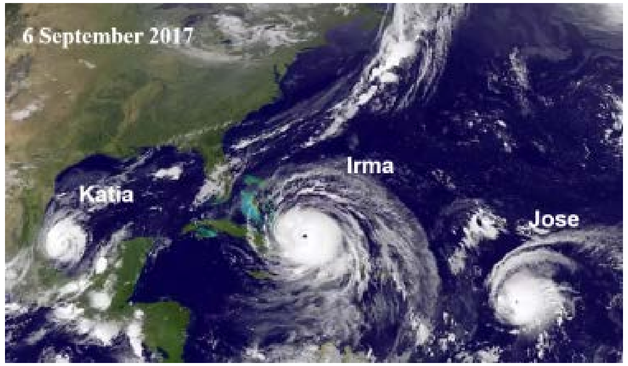
Non-symmetric, bimodal



Symmetric, bimodal

New Method of Analysis – “Extreme Value Analysis (EVA)”

- ***“Statistical extreme value theory** is a field of statistics dealing with extreme values, i.e., large deviations from the median of probability distributions.”* (Rieder, Harald E. "Extreme Value Theory: A primer." *Lamont-Doherty Earth Observatory* (2014).
- *“In EVA concepts like mean and variance are irrelevant because they don’t speak to the tail of the distribution Similarly, correlation isn’t the best measure of dependence because it is based on deviation around the means”* (Reich, NCSU, 2016, Overview of EVA” https://www4.stat.ncsu.edu/~reich/talks/Rossby.pdf)
- *The first step in classic EVA is to separate extreme observations from the bulk of the distribution For example, in a daily time series of precipitation in FL these correspond to very different weather regimes*
  - *Bulk: Thunderstorms*
  - *Tails: Hurricanes*



NOAA Image from https://www.washington.edu/news/2017/12/11/qa-uws-shuyi-chen-on-hurricane-science-forecasting-and-the-2017-hurricane-season/

Mean regression focus on thunderstorms and treats hurricanes as outliers. If you want to estimate the 100-year storm, you should focus only on hurricanes” (Reich, 2016)

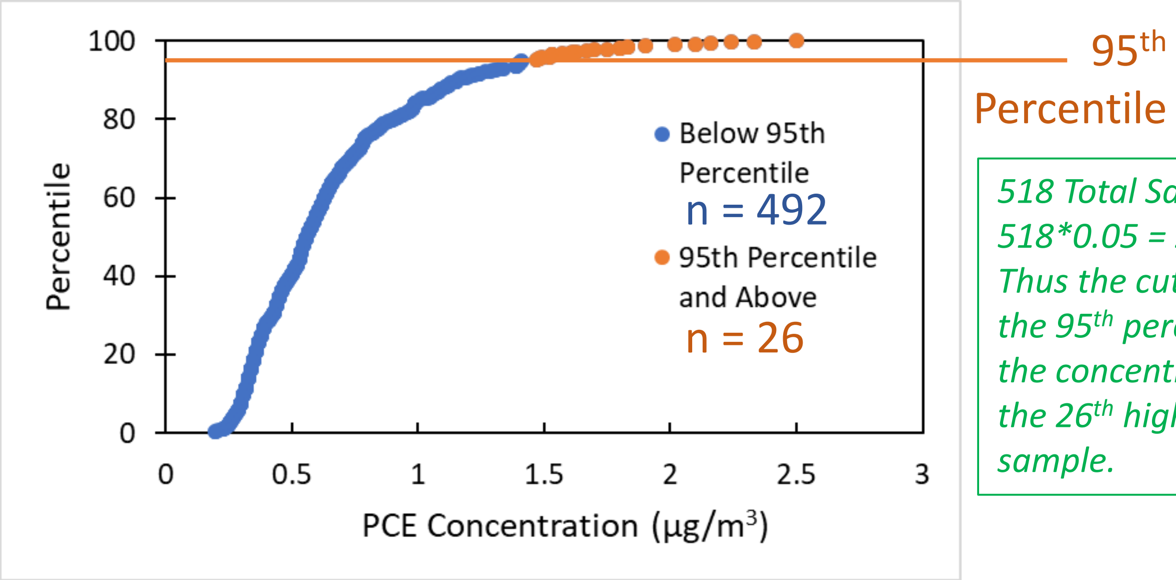
- *So here we isolate in on the >95%ile VOC events and ask what conditions predict them*

Methods for Extreme Value Analysis and Indicator Analysis Were Applied to Several Case Studies

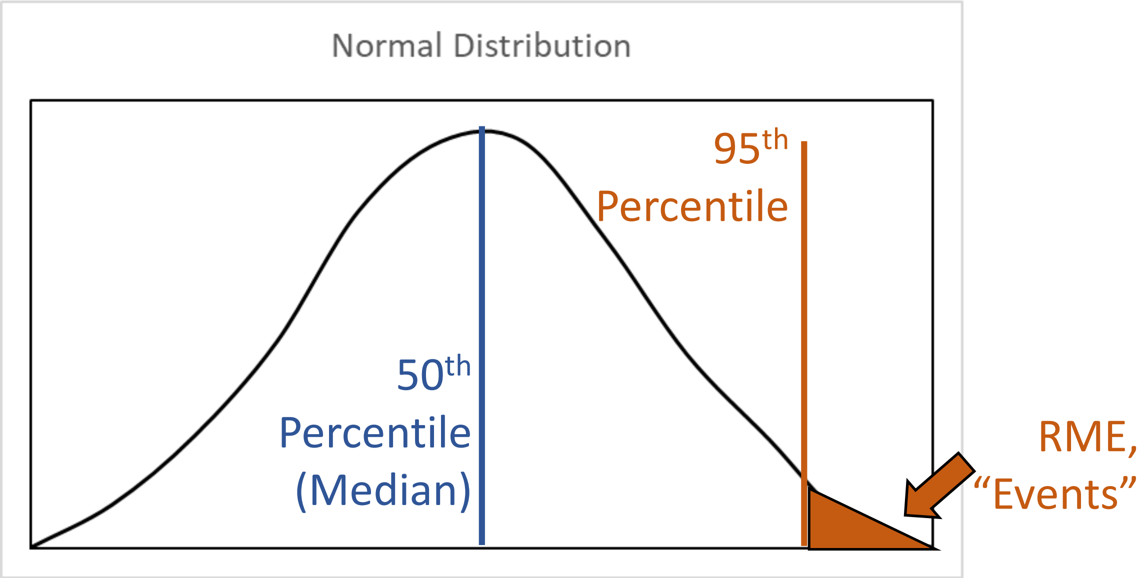
- The overall trends of predictor variables (i.e. meteorological variables) and outcome variables (VOCs) have been introduced in previous workshops for many of these cases.
- A.J. is going to introduce how we did extreme value analysis of these data sets and presented the results as box and whiskers plots
- The case study presenters will then combine both the extreme value analysis and the conventional analysis of what causes the full range of VOC concentrations in their discussions.

How We Did Extreme Value (RME) Analysis

- We ranked concentrations of chlorinate compounds by their 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 RME 95th percentile level.
- We classify all RME values as "Events"

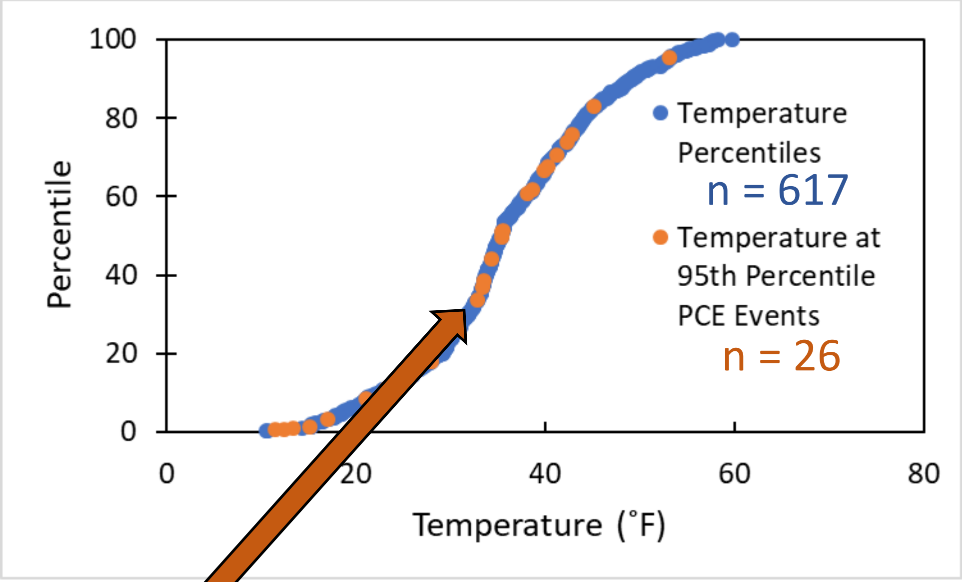


*518 Total Samples: 518*0.05 = 25.9 Thus the cutoff for the 95th percentile is the concentration of the 26th highest sample.*

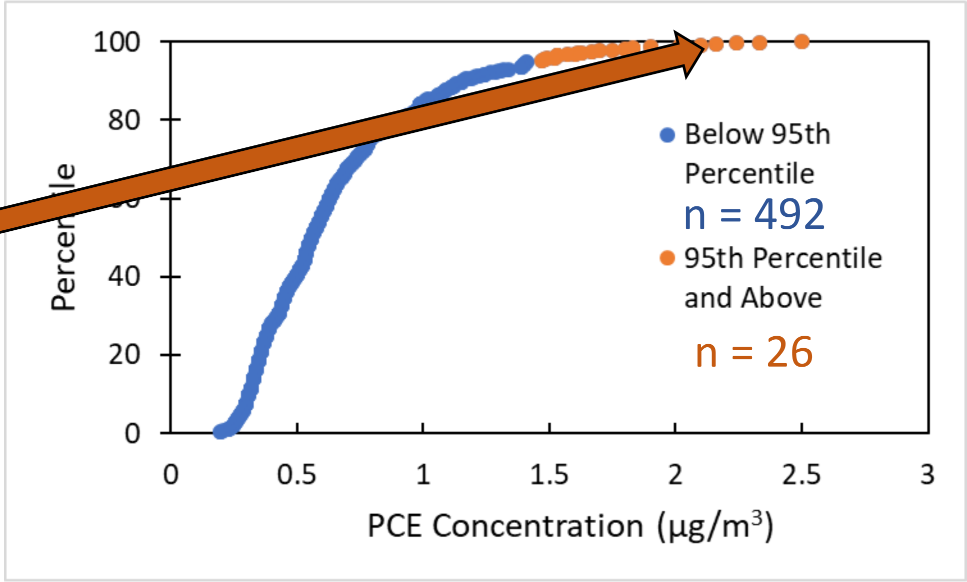


How We Did Extreme Value (RME) Analysis

- We calculated percentile rankings for each potential ITS based on its full distribution.
- We then examined the ITS percentiles for each time point where VOC >95%
- For example, the set of VOC concentrations above the 95th percentile is associated with a set of outdoor temperatures observed at the same time. The temperature distribution of this set can be widely spread (no correlation); or it could be narrow (correlation).



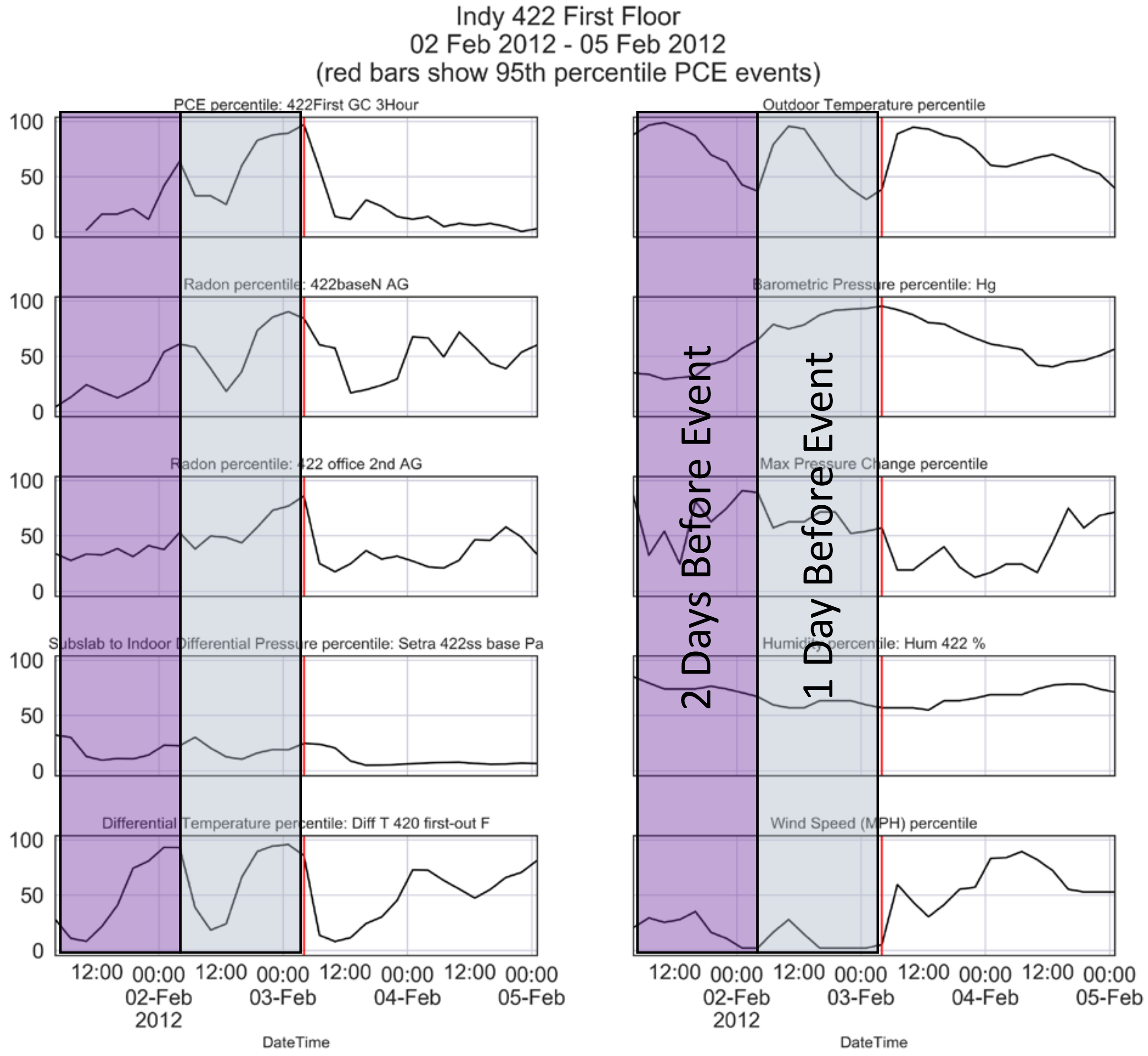
Date	Time	PCE Concentration (µg/m³)	PCE Percentile	Temp (˚F)	Temperature Percentile	Barometric Pressure (in Hg)	Barometric Pressure Percentile
2/2/2012	16:00	0.63	60.0	41.8	72.9	[illegible]	87.4
2/2/2012	19:00	0.98	82.8	35.6	52.2	[illegible]	91.6
2/2/2012	22:00	1.09	87.6	33.6	39.1	30.4092	92.4
2/3/2012	1:00	1.13	89.3	31.6	29.4	30.4190	93.2
2/3/2012	4:00	1.61	97.1	33.6	38.6	30.4492	95.3



How We Did Extreme Value (RME) Analysis

Each PCE data point can be assigned a percentile based on where it fits in the whole PCE data set.

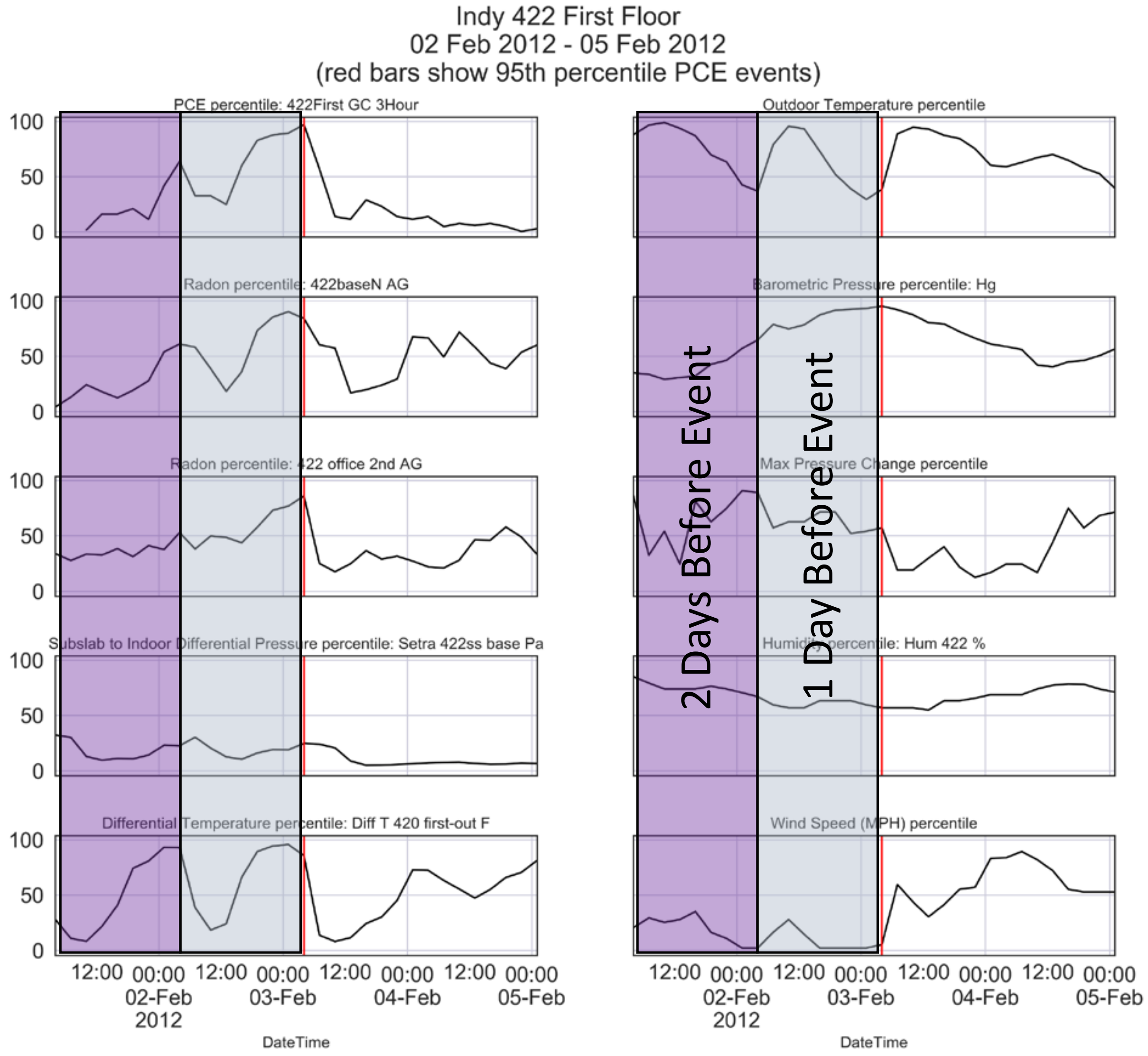
- We want to understand how ITS varies through time
- To do this, we reclassify the data based on the amount of time before a 95th percentile PCE event
  - Red line shows the 95th percentile event
  - Grey box shows 24 hours (1 day) before event
  - Purple box shows 2 days before event



How We Did Extreme Value (RME) Analysis

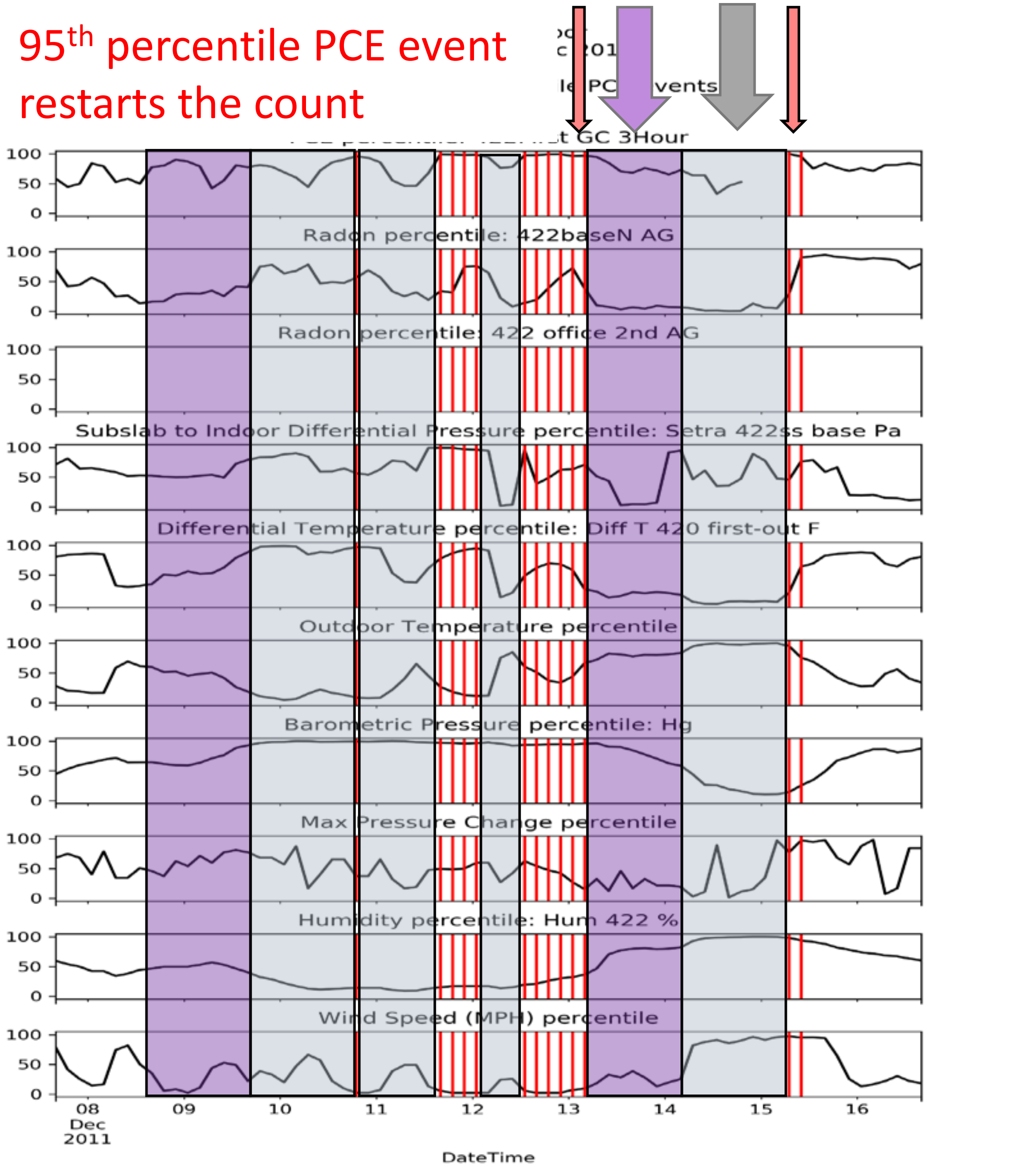
Each PCE data point can be assigned a percentile based on where it fits in the whole PCE data set.

Date	Time	PCE Concentration (µg/m^3)	PCE Percentile	Days Before Event
2/1/2012	10:00	0.25	1.9	2
2/1/2012	13:00	0.34	16.3	2
2/1/2012	16:00	0.34	16.3	2
2/1/2012	19:00	0.36	21.1	2
2/1/2012	22:00	0.32	11.6	2
2/2/2012	1:00	0.51	41.9	2
2/2/2012	4:00	0.66	63.7	1
2/2/2012	7:00	0.44	32.7	1
2/2/2012	10:00	0.44	32.7	1
2/2/2012	13:00	0.38	24.9	1
2/2/2012	16:00	0.63	60.0	1
2/2/2012	19:00	0.98	82.8	1
2/2/2012	22:00	1.09	87.6	1
2/3/2012	1:00	1.13	89.3	1
2/3/2012	4:00	1.61	97.1	0



How We Did Extreme Value (RME) Analysis

- We repeat this daily classification for each event within a dataset
- When multiple events happen in close succession, we restart our count of days before an event



Each PCE concentration above the 95th percentile is flagged ("the event") and the data sets for the days leading to the event are reviewed.
The procedure is repeated for each event over the whole time period studied.

How We Did Extreme Value (RME) Analysis

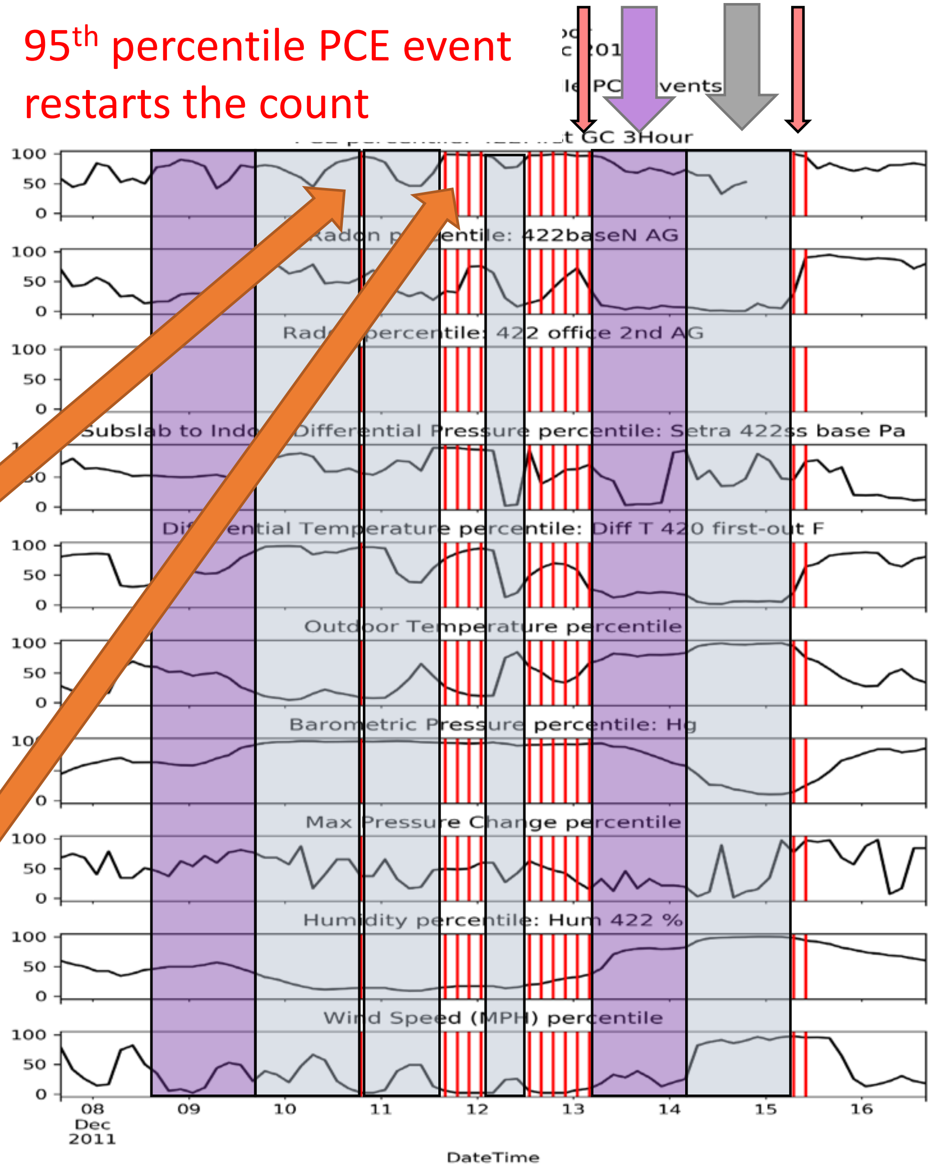
Date	Time	PCE Concentration (µg/m^3)	PCE Percentile	Days Before Event	Hours Before Event
12/10/2011	7:00	0.25	44.4	1	12
12/10/2011	10:00	0.34	71.9	1	9
12/10/2011	13:00	0.34	85.8	1	6
12/10/2011	16:00	0.36	90.4	1	3
12/10/2011	19:00	0.32	95.9	0	0
12/10/2011	22:00	0.51	93.4	1	15+
12/11/2011	1:00	0.66	85.8	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

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



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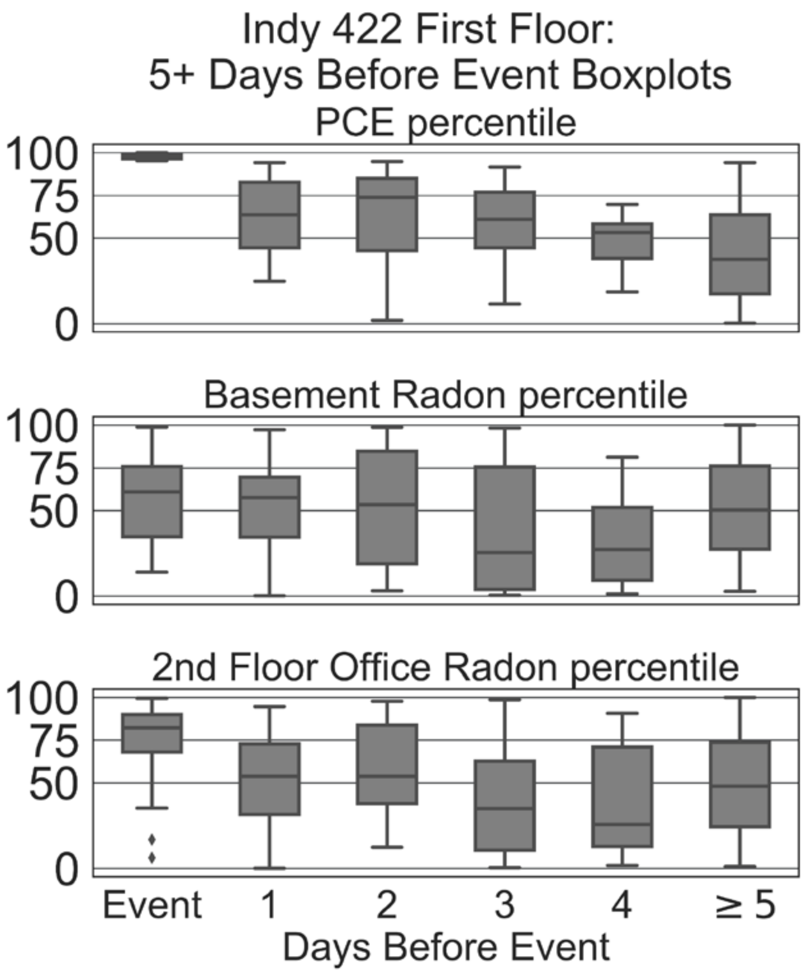
How We Did Extreme Value (RME) Analysis



26 red bars shown here show 95th percentile and above PCE Events.

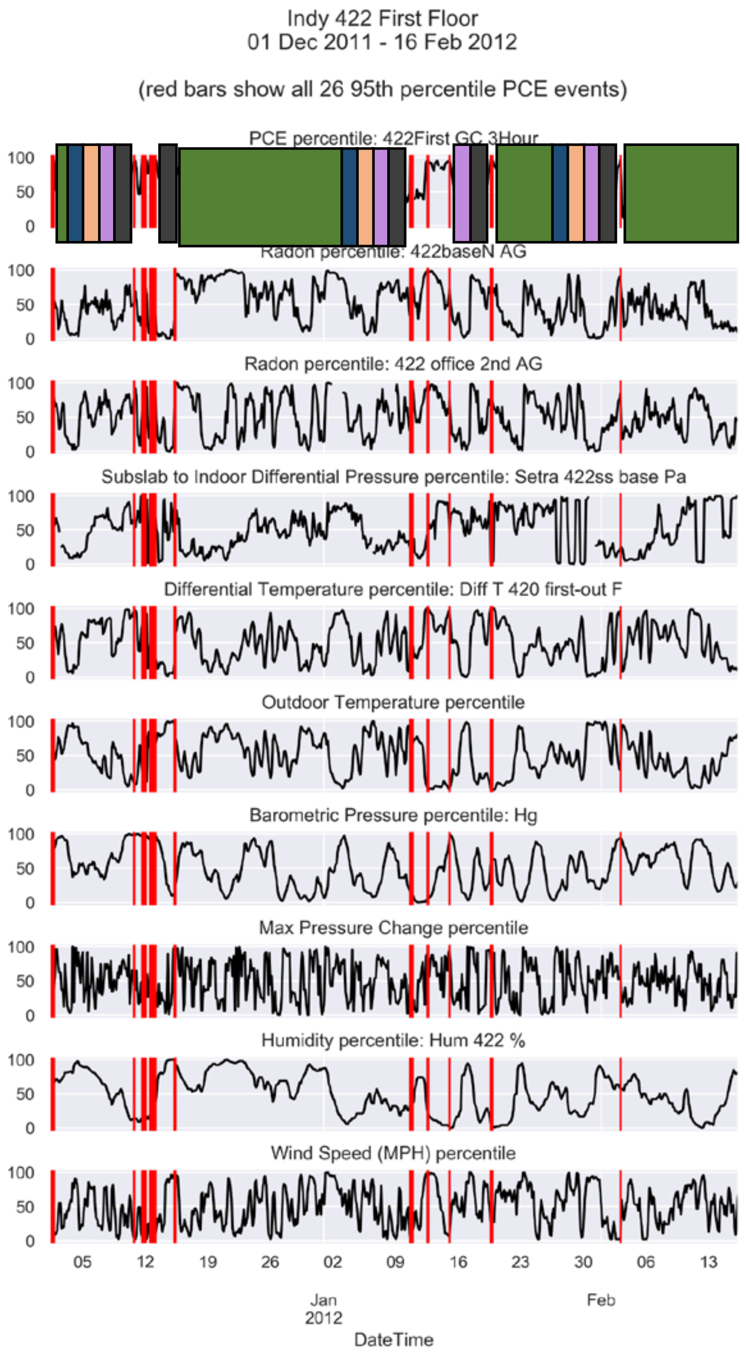
Grey bars are the time periods one day before an event,

Purple bars are the time periods two days before an event.

Orange bars are the time periods three days before an event.

Blue bars are the time periods four days before an event.

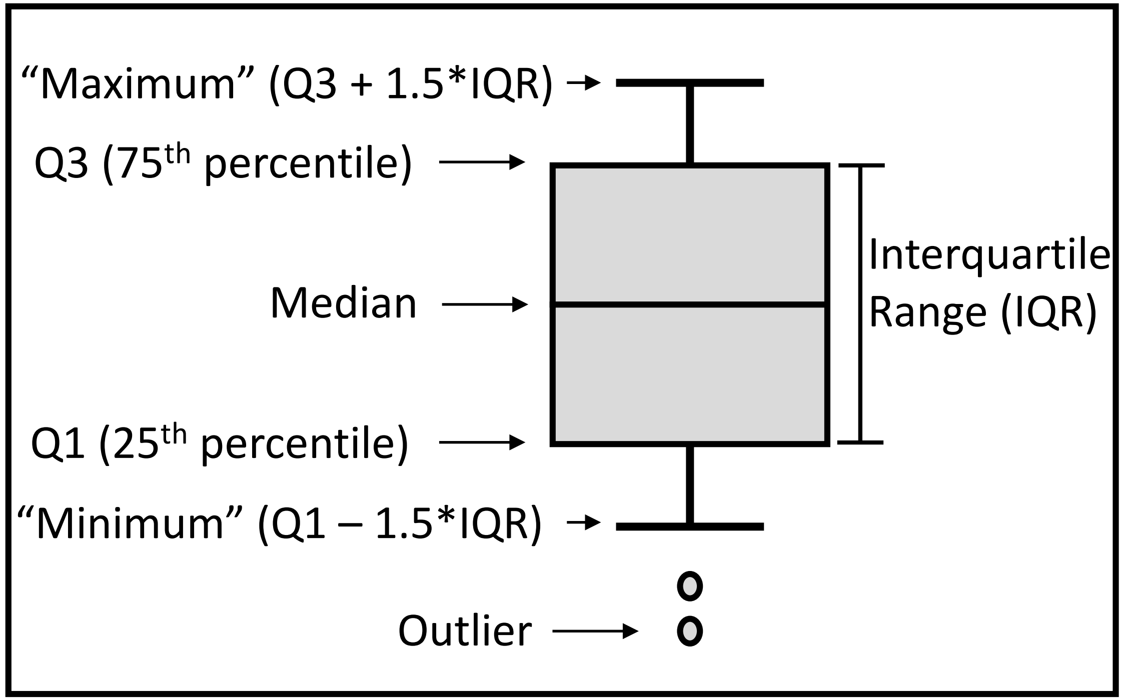
Green bars are for all the time 5 days or more before an event.

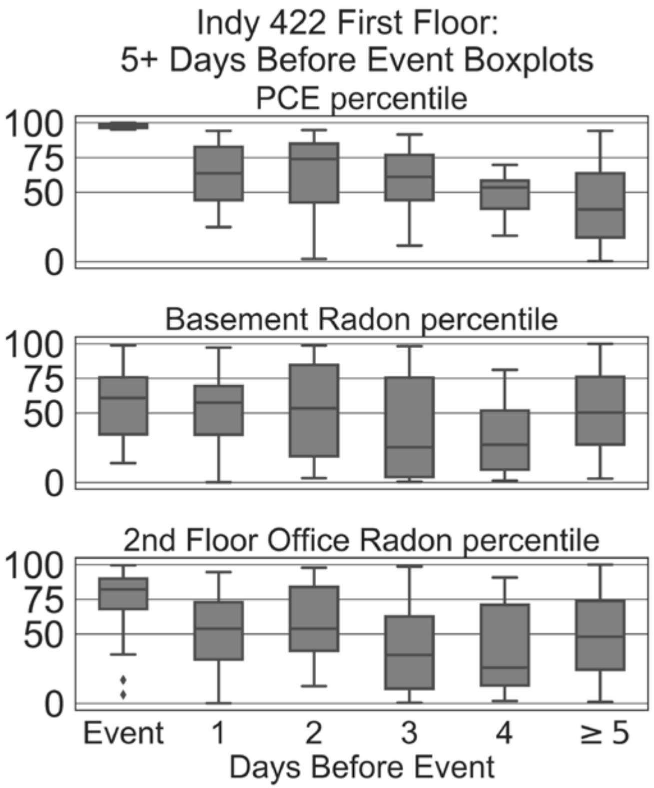


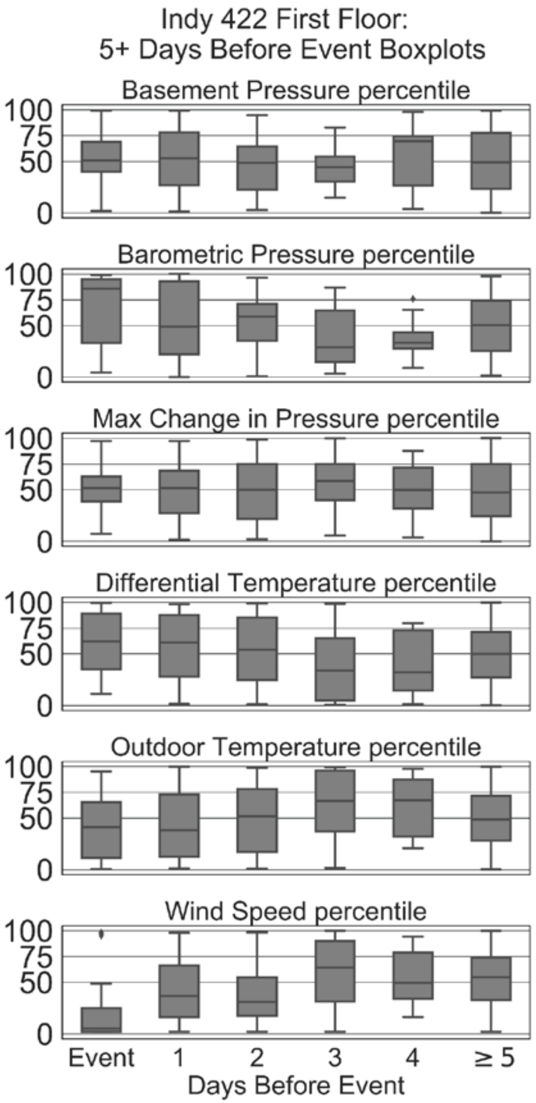
How We Did Extreme Value (RME) Analysis

- Finally, we aggregate the data based on the daily classification and present it as a new figure

Reading a boxplot:







Data Sets Analyzed

For example 1282 samples were collected at VA Site A location 26_08.
1282 * 0.05 ≈ 65 samples.
So we studied what conditions led to those 65 high samples.

Site/sampling location	Number of VOC data points	VOC Sampling Start Date	VOC Sampling End Date	Frequency used in analysis	Percentile used	Number of points > then that percentile. aka "Events"
VA Site A 26_08	1282	5/16/2019	1/10/2020	3 hr	95th	65
VA Site A 26_11	1278	5/16/2019	1/10/2020	3 hr	95th	64
Sun Devil Manor	342	10/14/2010	8/21/2012	24 hr	95th	18
Moffett	156	1/9/2004	2/6/2004	24 hr	95th	8
Gaffney	27	3/4/2019	12/23/2019	3-24 day periods	85th	4
Indy 422 Basement	518	12/1/2011	2/16/2012	3 hr	95th	26
Indy 422 First Floor	518	12/1/2011	2/16/2012	3 hr	95th	26

Data for the Indicators, Tracers and Surrogates was gathered over similar time ranges and used to calculate percentiles for those parameters.

Practical Questions Case Studies Can Address – Temperature and Pressure

- Does the temporal trend of exterior temperature (T) or indoor/outdoor T differential (ΔT) reliably predict volatile organic chemical (VOC) vapor intrusion (VI) in a given structure?
- Does that relationship have the same form/shape in different climates/site/building types?
- Does the temporal trend of measured differential pressure (indoor/outdoor ΔP; subslab/indoor ΔP) reliably predict VOC VI in a given structure?
- How much ΔP variability is typical?
- How much baseline data do you need to understand ΔP drivers for a building?
- Can the ΔP driver be predicted based on observed or forecasted barometric pressure (BP)? (So we can then read the weather forecast and know when the VI driving force will be "on")

Practical Questions Case Studies Can Address - Radon

- Does the temporal trend of radon (Rn) indoors reliably predict VOC VI in a given structure?
- How much indoor Rn variability is typical?
- How much Rn baseline data do you need to understand a building sufficiently to use Rn to guide VOC sampling times?
- Does the spatial trend of Rn indoors reliably predict VOC VI in a single building? multifamily unit? Large building? Across a neighborhood/plume?
- How much indoor Rn spatial variability is typical?
- Can the attenuation factor of Rn in soil gas (exterior or sub-slab) be used to accurately estimate the indoor conc. of VOC when Rn & VOC were both simultaneously collected from the same near building soil gas?

Review Paper Published, Reprints Available on Request from Authors

- Schuver, H.J., C. Lutes, J. Kurtz, C. Holton and R.S. Truesdale "*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, Published on line June 6, 2018, Volume 38, Issue 3; p 7-31.

Characteristics of the US Population of Buildings

Basic Divisions of US Buildings

- Commercial buildings – 5.6 Million buildings covering 87 billion square feet in 2012 http://css.umich.edu/factsheets/commercial-buildings-factsheet
- Total Housing Structures (2017 American Housing Survey) 121.5 Million
  - 76.8 Million single detached unit
  - 8.9 Million single attached unit
  - 8.3 Million 2 to 4 unit structures
  - 15.1 Million with 5 to 49 units
  - 5.4 Million with 50 or more units
  - 6.7 Million manufactured/mobile home or trailer
  - https://www.census.gov/programs-surveys/ahs.html

Separately the 2010 total of housing floor space in the US was estimated at 235 billion square feet Moura, Maria Cecilia P., Steven J. Smith, and David B. Belzer. "120 years of US residential housing stock and floor space." *PloS one* 10, no. 8 (2015).

Table of Square footage of housing units (thousands of units)

	Square Footage									
Total	Less than 500	500 to 749	750 to 999	1,000 to 1,499	1,500 to 1,999	2,000 to 2,499	2,500 to 2,999	3,000 to 3,999	4,000 or more	Not Reported
Estimate	Estimate	Estimate	Estimate	Estimate	Estimate	Estimate	Estimate	Estimate	Estimate	Estimate
121,560	2,765	7,702	13,808	27,730	22,203	14,554	7,828	7,333	3,555	14,081

Size Characteristics of US Commercial Buildings (2003)

Building Floorspace (square feet)	Number of Buildings (%)	Total Floorspace (%)
1,001 to 5,000	53	10
5,001 to 10,000	20	10
10,001 to 25,000	17	18
25,001 to 50,000	5	13
50,001 to 100,000	3	14
100,001 to 200,000	2	14
200,001 to 500,000	1	10
Over 500,000	0	11

Census Bureau/Energy Information Agency data, converted to percentages
https://www2.census.gov/library/publications/2011/compendia/statab/131ed/tables/12s1006.pdf

Age Distribution of US Commercial Buildings as of 2003

	Number of Buildings (%)	Total Floorspace (%)
Year Constructed		
Before 1920	7	5
1920 to 1945	11	10
1946 to 1959	12	10
1960 to 1969	12	12
1970 to 1979	16	17
1980 to 1989	16	17
1990 to 1999	19	20
2000 to 2003	7	9

Data from:
https://www.eia.gov/consumption/commercial/data/archive/cbecs/cbecs2003/detailed_tables_2003/detailed_tables_2003.html; converted to percentages

How Common are Unheated Commercial Buildings?

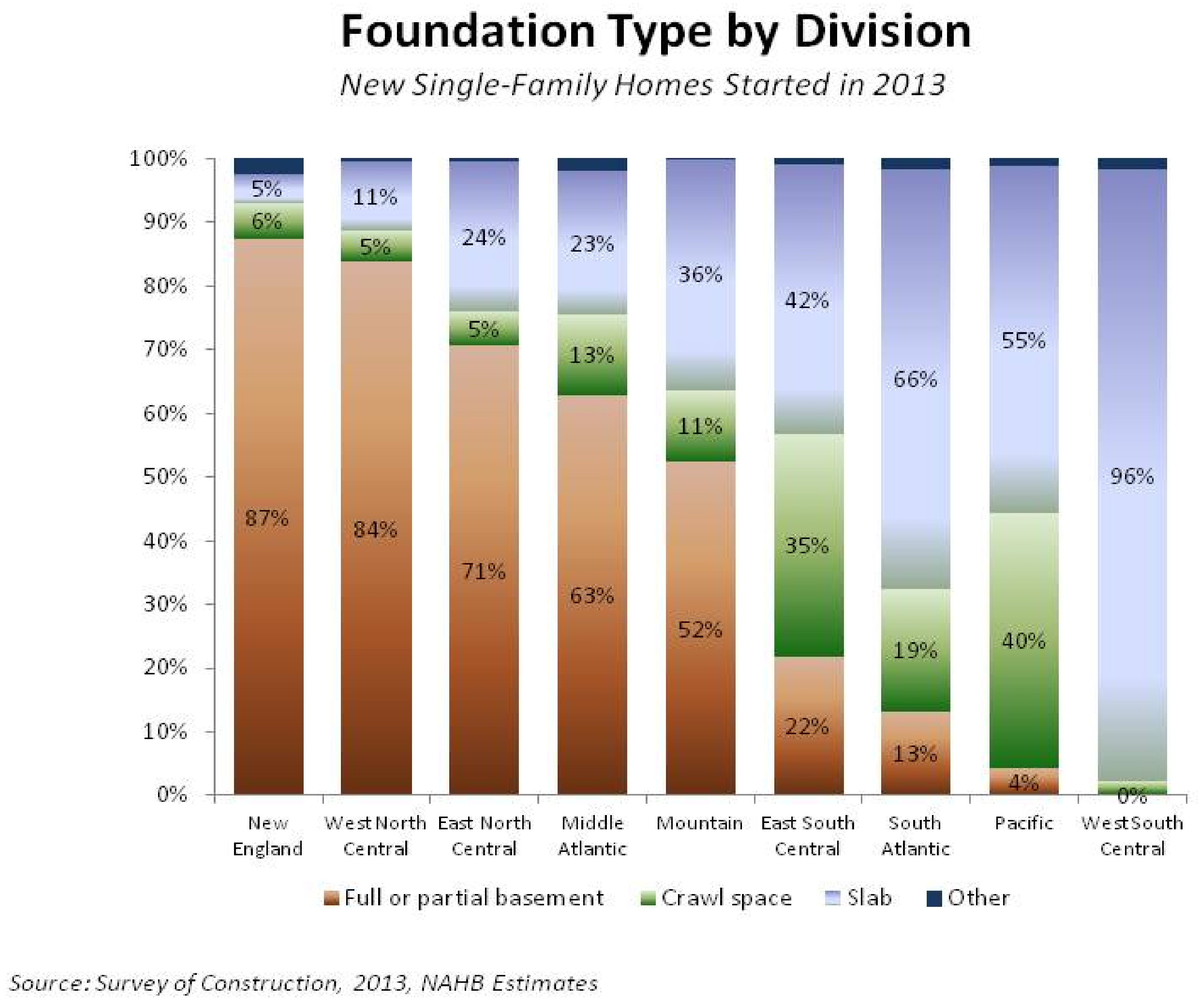
	Number of Buildings (percentage)				Total Floorspace (percentage)			
	Not Heated	1 to 50 Percent Heated	51 to 99 Percent Heated	100 Percent Heated	Not Heated	1 to 50 Percent Heated	51 to 99 Percent Heated	100 Percent Heated
All Buildings*	14	11	11	64	7	11	13	70
Census Region								
Northeast	7	10	12	71	2	11	12	75
Midwest	12	9	11	67	4	7	10	79
South	18	13	9	60	11	12	12	65
West	16	11	12	61	11	13	17	59
Climate Zone: 30-Year Average								
Under 2,000 CDD and --								
More than 7,000 HDD	12	11	11	65	5	10	13	72
5,500-7,000 HDD	10	9	10	71	4	6	10	80
4,000-5,499 HDD	7	13	12	68	2	12	15	71
Fewer than 4,000 HDD	18	11	12	59	11	12	15	62
2,000 CDD or More and --								
Fewer than 4,000 HDD	26	13	9	53	17	15	10	58

(Data from 2003 Energy Information Agency Survey) – Percentages calculated by Lutes
https://www.eia.gov/consumption/commercial/data/archive/cbecs/cbecs2003/detailed_tables_2003/detailed_tables_2003.html

How Common Are Various Heating Systems in US Commercial Buildings? - 2003

Number of Buildings (percentage)								
		Heating Equipment (more than one may apply)						
All Buildings*	Heated Buildings	Heat Pumps	Furnaces	Individual Space Heaters	District Heat	Boilers	Packaged Heating Units	Other
100	86	10	40	18	1	12	21	4
Primary Space-Heating								
Energy Source								
Electricity	27	8	6	7		1	9	1
Natural Gas	43	2	26	8		8	10	1
Fuel Oil	6		3	1		3		
District Heat	1	0		0	1		0	
Propane	7		4	2			1	
Other	2							

(Data from 2003 Energy Information Agency Survey) – Percentages calculated by Lutes
https://www.eia.gov/consumption/commercial/data/archive/cbecs/cbecs2003/detailed_tables_2003/detailed_tables_2003.html

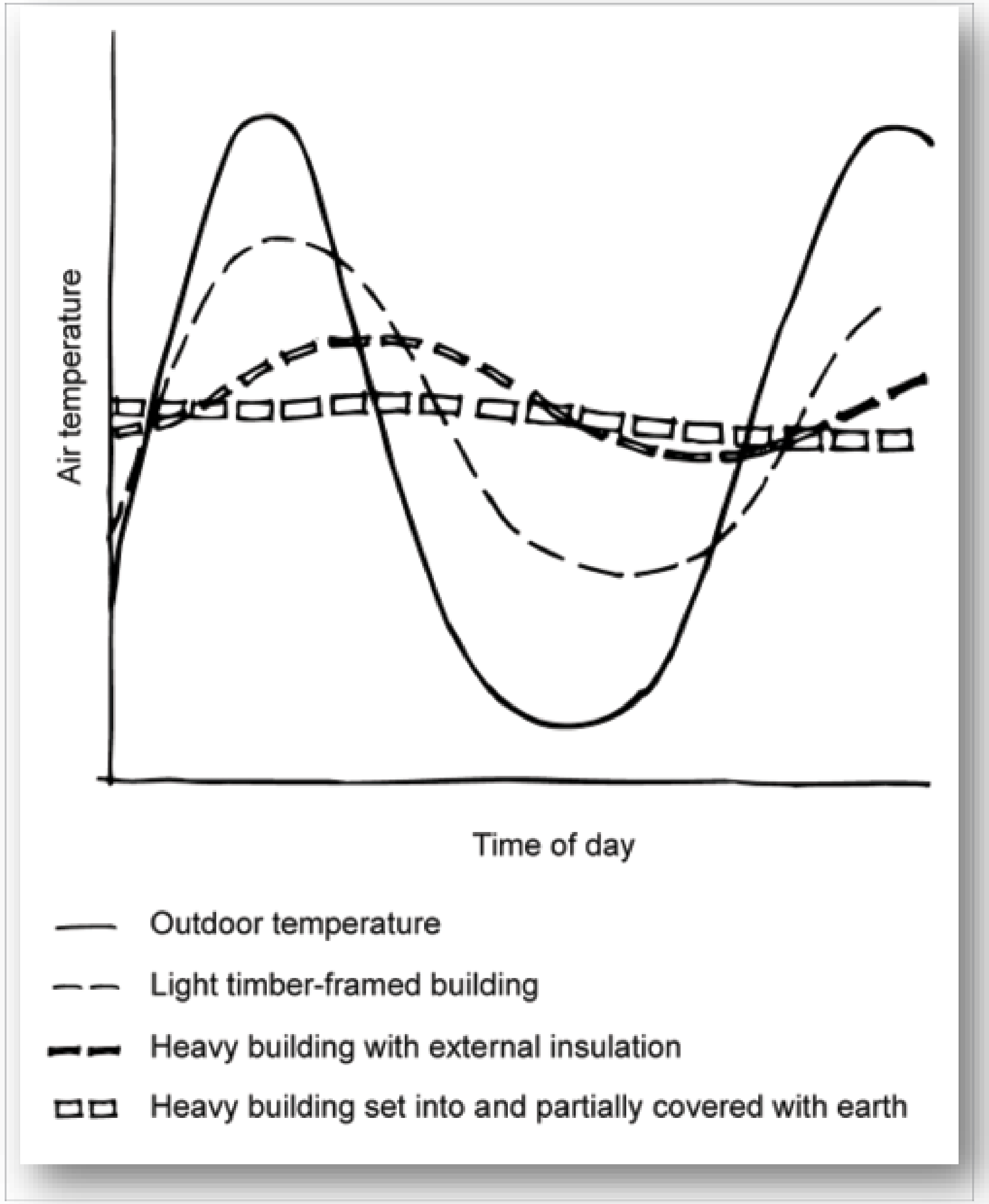


Foundation Type Varies with Region

National Association of Homebuilders: http://eyeonhousing.org/2014/10/what-foundations-are-built-across-the-nation/

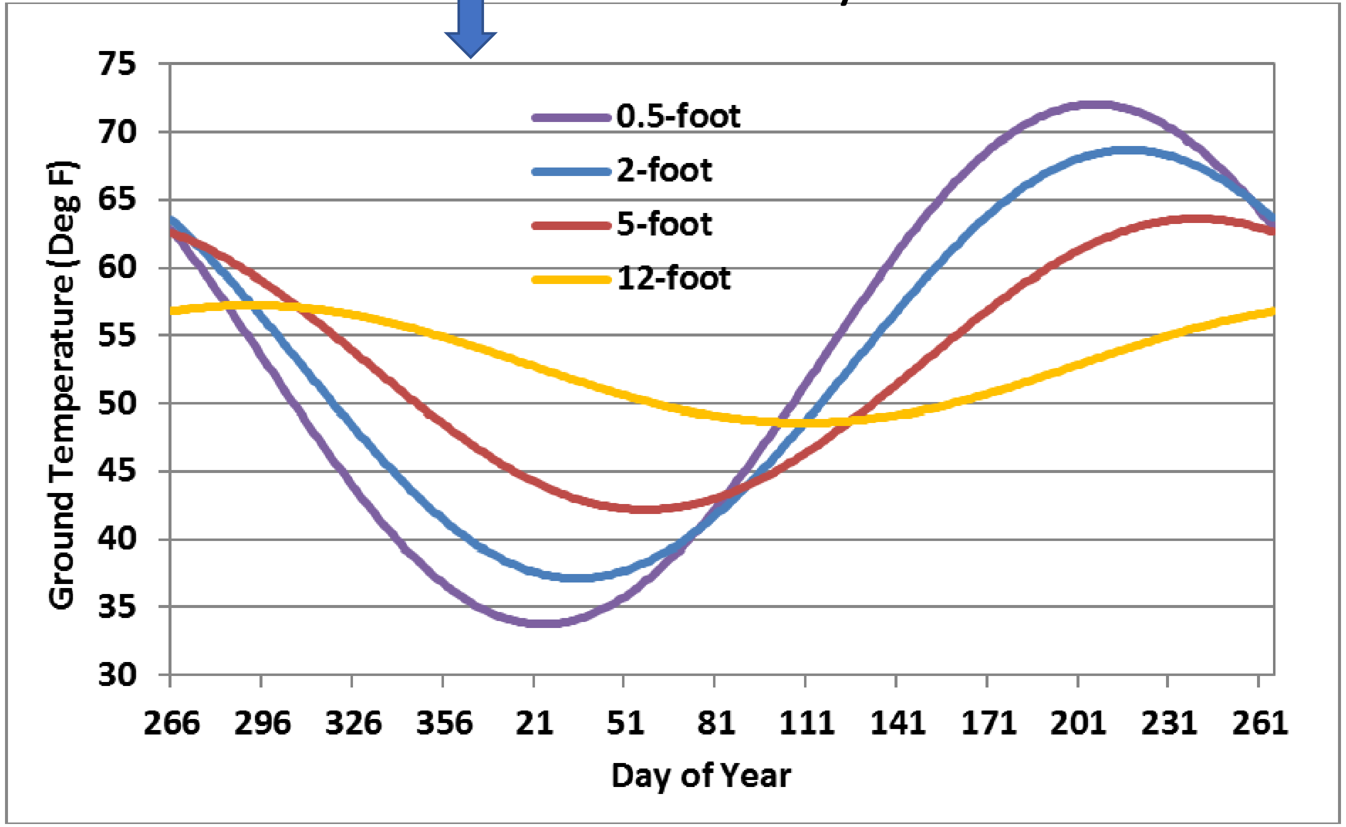
Some Key Concepts

The Importance of Thermal Mass



Diurnal cycle in buildings drives indoor/outdoor temperature differential.

Annual Cycle in Soil



Above Graphic from: https://igws.indiana.edu/Geothermal/HeatPumps

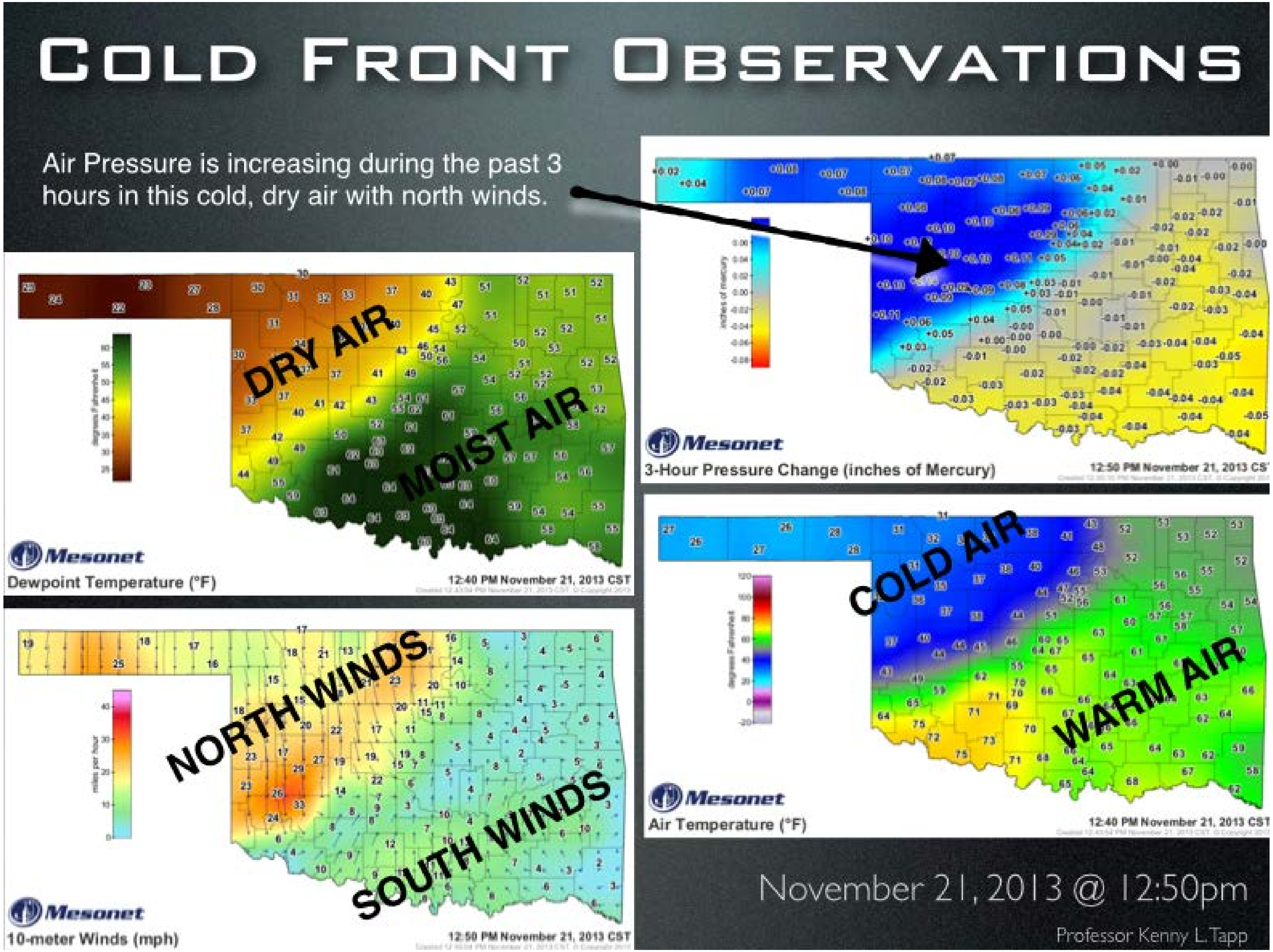
Left Graphic from: http://www.yourhome.gov.au/passive-design/thermal-mass

Temperature, Pressure and Precipitation Events are All Linked When a Front Passes

During a Cold Front passage:

- Air Temperature **Decreases**
- Dewpoint Temperature (Moisture) **Decreases**
- Wind shift from South to North
- Air Pressure **Increases**

Reprinted from: http://www.occc.edu/ktapp/gophysics/PHYS1014/AirMassFronts.htm (Oklahoma City Communit College)

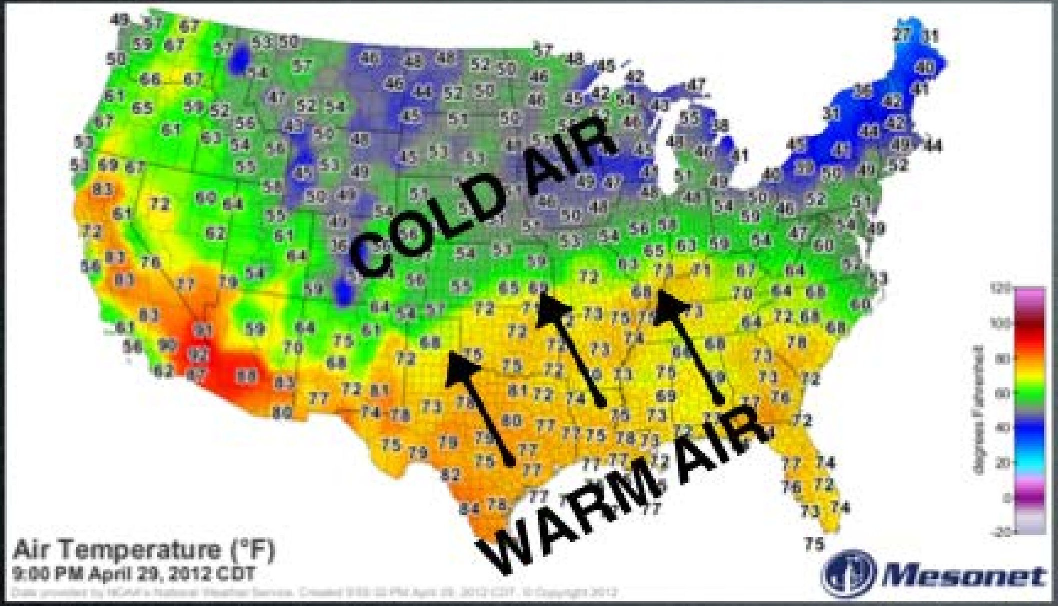


Warm Front Observations

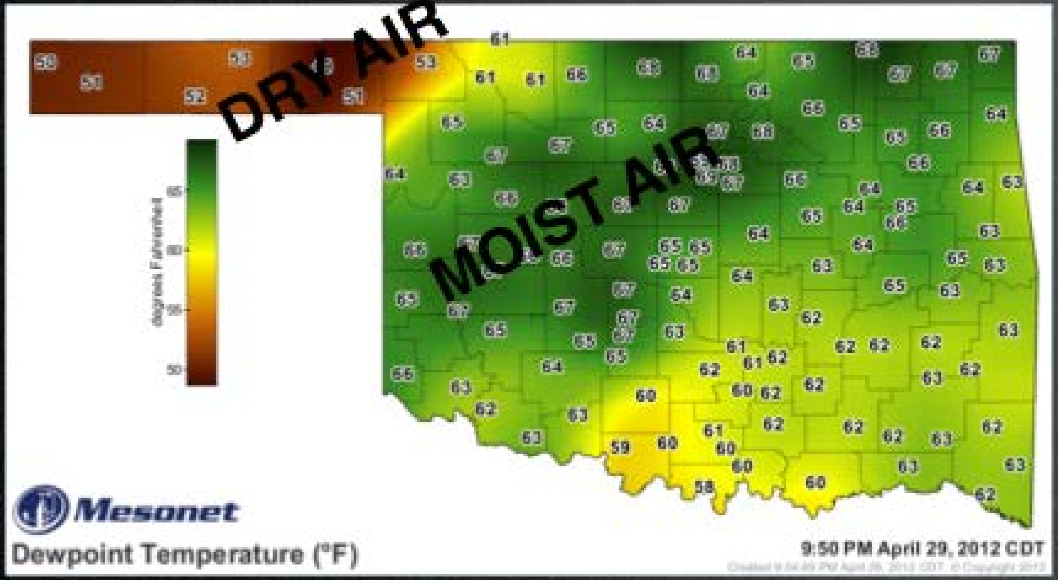
Temperature, Pressure and Precipitation Events are All Linked When a Front Passes during a Warm Front passage:

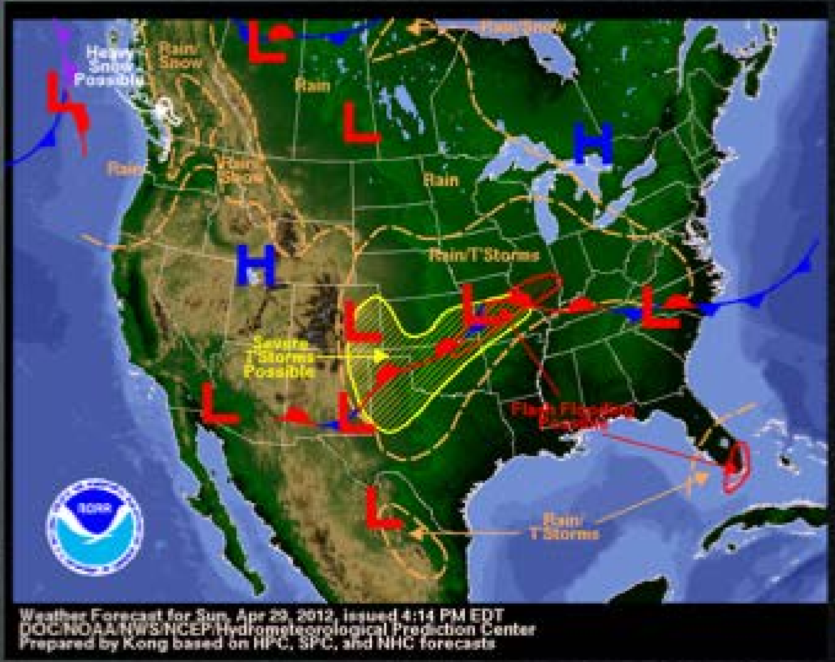
- Air Temperature **Increases**
- Dewpoint Temperature (Moisture) **Increases**
- Air Pressure **Decreases**

Reprinted from: http://www.occc.edu/ktapp/gophysics/PHYS1014/AirMassFronts.htm (Oklahoma City Communit College)



Warm, moist air is surging northward through Oklahoma into Kansas. The weather forecast map below depicts the warm front as a focus of creating rain in the area outlined in yellow.



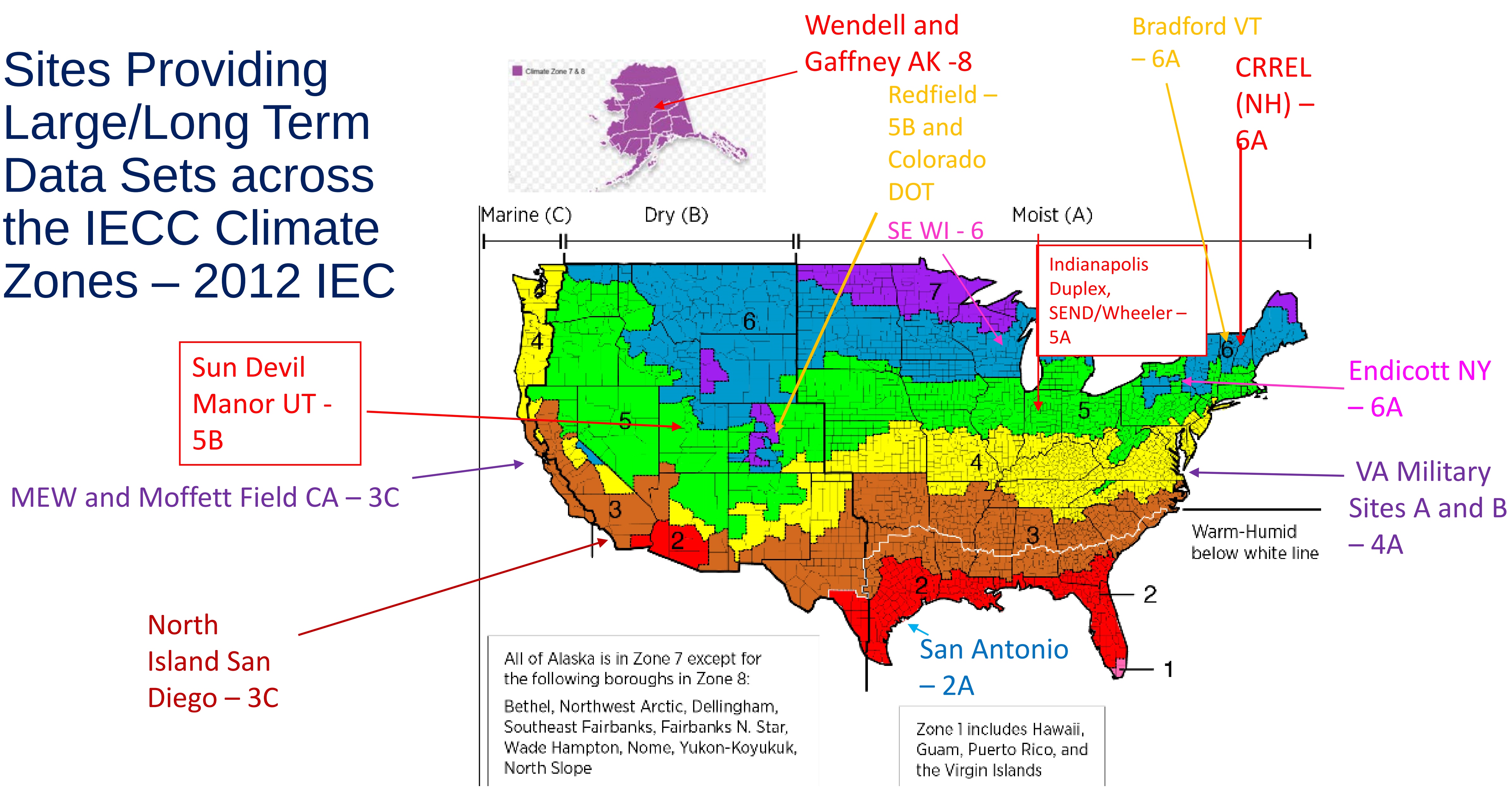


April 29, 2012 @ 9:00pm

Professor Kenny L. Tapp

Case Studies

Sites Providing Large/Long Term Data Sets across the IECC Climate Zones – 2012 IEC



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