Chapter 1

The Significance of Foundation Entry Mechanism on Vapor Intrusion

1.1 Summary

This chapter explores the importance of dominant transport mechanism for contaminant vapors entry into a building. There are two commonly accepted mechanisms by which contaminants enter a building from the soil beneath it – advection and diffusion. In the case of advection, contaminant is carried into a building as a constituent of soil gas, which is swept into the building by a pressure gradient from soil to building interior. Such gradients need not be large and a few Pa can drive such a flow. On the other hand, if the interior of the structure is pressurized relative to the sub-foundation soil, then the advective flow will be out of the building. Regardless of the existence or direction of a pressure gradient, there generally exists a contaminant concentration gradient from soil into the structure, which means that there will always be a driving force for diffusive entry of the contaminant into the building. Only if the outward advective flow is high enough can this diffusive entry be overcome, and contaminant entry prevented. Advective transport is likely to only be dominant

at VI site with some feature or pathway that allows facile delivery of air (soil-gas) the entry point in the foundation. This is because there is generally a large resistance to transport of soil gas through the surrounding soil, bearing in mind that the pressure gradients available to drive any flows are normally quite small. It has been shown in previous modeling studies that for quite comparable levels of contaminant vapor beneath the foundation slab, very different indoor air contaminant concentrations may be encountered, depending upon the ability of the surrounding soil to allow significant advective flow[**bozkurt˙simulation˙2009**, **pennell˙development˙2009**]. This fact emphasizes the importance in vapor intrusion investigations of identifying features that will allow significant advective flow from soil to the building interior. When advective entry is the dominant mode of contaminant entry into a building, use of building pressurization (in a controlled pressure method, (CPM) study) as an investigative tool is likely to offer more definitive results than when diffusive entry is dominant. The existence of an advective entry dominated scenario also may enable using weather (e.g., barometric pressure or wind) and temperature as predictors of building pressurization and from that, contaminant entry rates. Historically, the most widely held view of vapor intrusion has been that it is advective entry dominated, and indeed at many sites that is the case. But where this assumption does not hold can lead to confusion when interpreting results.

1.2 Advective Entry: Role of Soil and Foundation

The modeling in Chapter **??** help to explain why building pressurization influenced indoor air contaminant concentrations much more before the closing off of the sub-slab preferential pathway than after the closure. The existence of the preferential pathway allowed advective transport to be the dominant transport mechanism for entry of contaminant vapors through the foundation breach. This finding has wider implications for our understanding of the entry mechanics of VI.

It is commonly assumed that advective transport dominates in the near-foundation region and through breaches in the foundation itself, but our modeling of the situation at the ASU house showed that this was mainly possible because:

1. The preferential pathway represented a source from where air could readily be drawn drawn into the subslab region.

2. The permeable gravel sub-base acted as a communication medium between the preferential air source and the building.

In other words, for advective transport to dominate through foundation cracks, some site-specific features were required. We showed that absent the preferential pathway, the soil surrounding the house itself presented too much resistance to air flow for this to be possible.

Only one soil type was explored in the modeling work in Chapter **??** - sandy clay. This kind of soil is a relatively impermeable soil, and other soil type are now considered. Furthermore, our modeled house featured a basement, and in such a scenario, the atmosphere is relatively far removed from the foundation breach, and thus it makes sense to also consider a slab-on-grade type of foundation.

The effect of different soil and foundation types is investigated using the model already introduced in Chapter **??**. We consider 12 of the soil types defined by the EPA (see Table **??**) and for each of these we consider a basement and a slab-on-grade case respectively. The basement and slab-on-grade cases are defined by the bottom of a foundation slab located at 1 m and 15 cm bgs respectively. The building is assumed to be depressurized at $p_{in} = -15\,\mathrm{Pa}$, a value somewhat greater than "normal", in order to enhance the advective entry potential. The analysis in Chapter **??** already showed that for the case of existence of a gravel sub-base layer, absent an air source supplied by a preferential pathway, results were was virtually indistinguishable from the cases where there was no gravel sub-base layer. I.e. a gravel sub-base will not be included in the model.

The results of the calculations will be shown in terms of the Péclet number for the modeled contaminant entry pathway. This Péclet number is defined as already shown before in equation (??) as:

$$\mathrm{Pe} = \frac{\text{advection}}{\text{diffusion}} = \frac{u_{\mathrm{ck}} L_{\mathrm{slab}}}{D_{\mathrm{g}}} \tag{1.1}$$

here u_{ck} [$\mathrm{m\,s^{-1}}$] is the airflow velocity across (through) the crack $L_{\mathrm{slab}} = 15\,\mathrm{cm}$ is the thickness of the foundation slab, i.e. the characteristic length for transport; and $D_g = 6.87 \times 10^{-6}\,\mathrm{m^2\,s^{-1}}$ is the diffusivity of TCE in air.

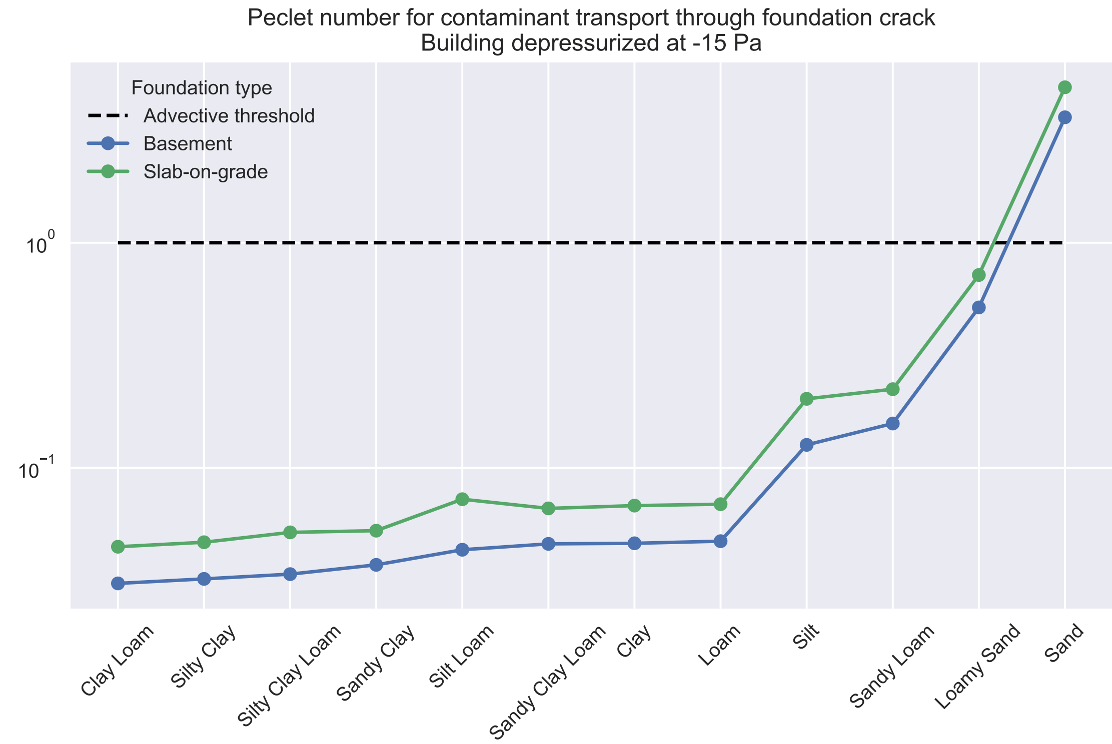


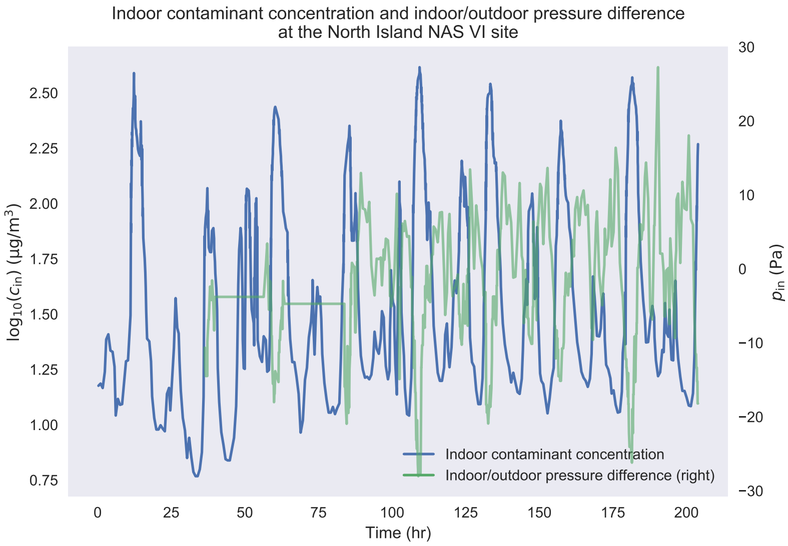
Figure 1.1: Predicted effect of soil and foundation type on the Péclet number of transport through the foundation crack. We consider the 12 different soils studied by the EPA (see Table), and for each of these we consider a house featuring a basement and a slab-on-grade house. The foundation slab is assumed to be 15 cm thick. In the basement case, the bottom of the foundation slab is assumed to be 1 m bgs and in the slab-on-grade case 15 cm bgs. The modeled building is assumed to be depressurized at $-15\,\mathrm{Pa}$. The threshold where advective contaminant entry begins to overtake diffusive entry, i.e $\mathrm{Pe} = 1$, is marked by the dashed line.

The result of these model calculations are shown in Figure 1.1. These results shows that for most soil types, irrespective of whether a building has a basement or a slab-on-grade foundation, the Péclet number across the foundation slab is actually not sufficiently high for advection to be the dominant entry mechanism; most soils are too impermeable for sufficient airflow to be pulled into the building by the small pressure gradient that exists between the building interior and the subsurface. Sites characterized by sandy soil are an exception to this, as they are permeable enough to sustain such airflows.

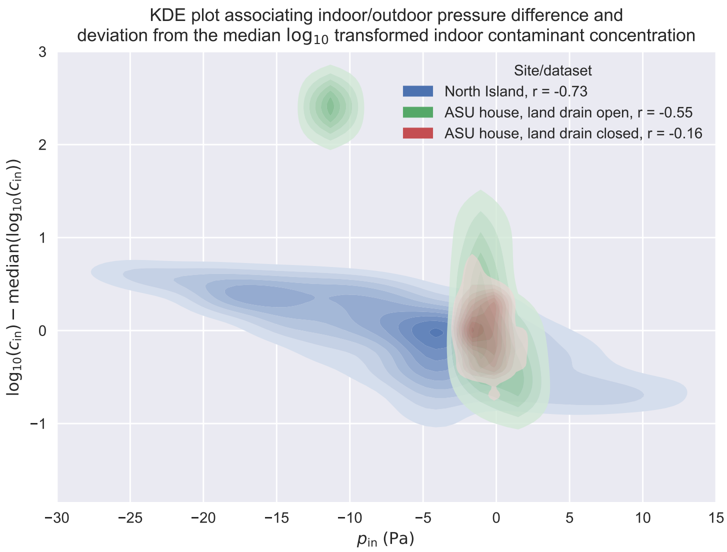
An example of such a site is a site at North Island Naval Air Station (NAS) in San Diego, California, characterized by sandy soil. There the indoor contaminant concentration and building pressurization were highly correlated[**hosangadi˙high-frequency˙2017**]. Figure 1.2 demonstrate this correlation by showing the fluctuating indoor contaminant concentration and building pressurization at North Island NAS over time. Figure 1.2 also includes a kernel density estimation (KDE) plot of the building pressurization and indoor contaminant concentration. The KDE plot and calculated Pearson's r values show that indoor contaminant concentration and building pressurization was even more strongly associated at North Island NAS than the ASU house when the preferential pathway was open. This strong correlation can partly be attributed to the sandy soil at the site, but also to the significant building pressurization fluctuations at the site (compared to the ASU house).

In contrast, **hers˙evaluation˙2014**[**hers˙evaluation˙2014**] studied a VI site in North Battleford, Saskatchewan, Canada, where they continuously monitored oxygen, pressure differentials, soil temperature, soil moisture, and weather conditions. The recorded data was used together with a reactive transport model (MIN3P-DUSTY) to simulate biodegradation and transport at the site. Together with analysis of the site data, they concluded that contaminant transport was dominated by diffusion, and little association between building pressurization and contaminant entry existed.

This indicates that for many sites characterized by other soil types, significant advective transport of contaminant vapors into the building is likely to be possible in the presence of some preferential air source. It is important to note however, that preferential pathways can be of many types, not just the one case that we have considered in Chapter **??**. For example, having a layer of loose, unconsolidated soil



(a) Time series of the indoor contaminant concentration and indoor/outdoor pressure difference at the North Island NAS VI site. A negative pressurization value here indicate that there is a net flow of air into the building.



(b) Kernel density estimation (KDE) plot of indoor contaminant concentration c_{in} and indoor/outdoor pressure difference p_{in} at North Island NAS and the ASU house (considering the periods when the land drain was open and closed respectively). Indoor contaminant concentrations are $\log_{10}$ transformed and normalized to their respective median values to allow comparison of how building pressurization contributed to indoor contaminant concentration variability. A deeper color indicates that the two variables are more closely associated. Pearson's r values of $\log_{10}(c_{\text{in}})$ and p_{in} for each dataset were also calculated.

Figure 1.2: Building pressurization and indoor contaminant concentration were highly correlated at the North Island Naval Air Station (NAS) VI site.

adjacent foundation walls might in some cases provide a low resistance pathway to flow of air to the subslab region.

The consequences of this analysis are important when considering the application or interpretation of certain types of vapor intrusion investigation strategies.

1.3 Applying Transport Classification Concept

Contaminant entry from the subsurface into the a building may be dominated by advection or diffusion and which it is dramatically changes how a structure is expected to respond to change in building pressurization. For diffusion dominated sites, contaminant entry rates will be relatively decoupled from building pressurization, except in the limit where the building is sufficiently pressurized relative to the subsurface that the diffusion pathway is effectively cut off. This has implications for a wide variety of VI investigation strategies, but is perhaps most relevant for attempting to use CPM and choosing the relevant ITS parameters for study.

1.3.1 The Controlled Pressure Method

The idea of CPM is to control internal building pressurization, e.g. by using some fans or blowers to induce a higher or lower than ambient pressure in the structure. The normal expectation is that this will in turn control the contaminant entry rate. The underlying assumption in application of this method is that contaminant entry into a building is largely advective in nature. Because the effect of minor pressure fluctuations on diffusion coefficients is negligible, the only effect that such a building pressure variation can have is in adjusting the advective flow that either promotes or impedes the diffusive flux. But as the preceding Péclet number analysis has already shown, most cases are quite far towards the limit of diffusion control, and so small changes in advective entry rates will have minor effects on diffusive entry rates. Thus at "diffusion-controlled sites" the CPM method will not be as effective.

Figure 1.3 further illustrates this point. Reconsidering the case of the ASU house analysis already discussed in Chapter **??**, during the period when the land drain preferential pathway was open, CPM dramatically increased indoor contaminant concentrations compared to the when the CPM system was inactive. However, after the closing of the land drain preferential pathway, CPM did not have any significant effect on measured indoor contaminant concentrations. From the modeling of this situation, it was deduced that the presence of the land drain preferential pathway made advection the dominant entry mechanism of contaminant vapors into the building. Once that pathway was closed, the influence of a significant depressurization of the building was rather muted, because the basic diffusive entry pathway was largely unaffected.

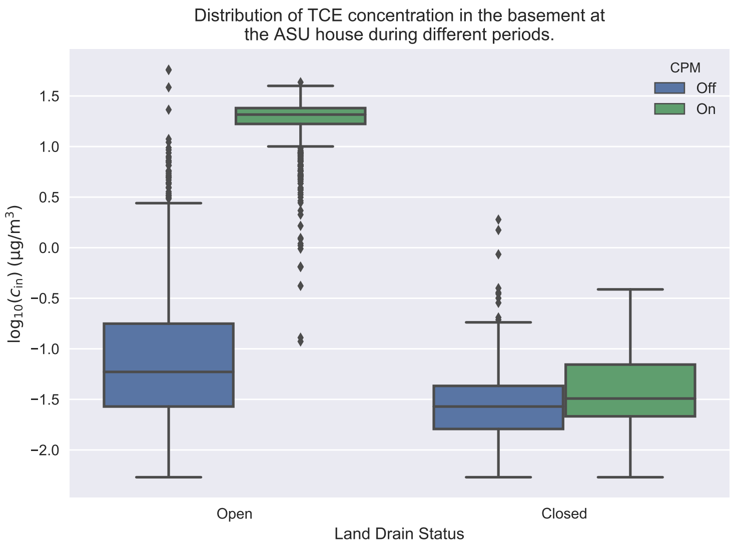


Figure 1.3: Boxplot showing the log-10 transformed TCE concentrations measured at the ASU house as a function of whether the preferential pathway was open or closed. The measured contaminant concentrations obtained during the reduced pressure CPM and "natural" vapor intrusion periods are considered separately. The box signifies the interquartile range (IQR) of values, with the central line representing the median value, and the top and bottom of the box are the 25th and 75th percentiles. The whiskers extend to 1.5 times the IQR. Markers indicate outlier data points that fall outside the whiskers.

The above results warn that depressurization of a structure using CPM might not lead to the expected result of a significant increase in entry rate of contaminant. Proponents of the technique argue that the method can offer a "worst possible case" result for a particular building, because the employed depressurization will be greater than anything that would naturally be encountered in the structure. This thinking is clearly influenced by a conceptual model that views advective entry as a dominant entry mode. The logic that such depressurization will offer a "worst possible case" result is actually not flawed, because enhancing contaminant entry rate is a real consequence of the depressurization. What will not be as apparent in the results from a diffusive entry limited case is that there is any relationship between the degree of depressurization and entry rate (and thus, indoor air concentration); there is a good chance that any small increase in concentration would be lost in the normal "noise" of such concentration measurements. The true value of the CPM can come in cases in which there is an obvious and large increase in entry rate with the degree of depressurization; in those cases, there will be a clear indication of either a permeable soil or the existence of a preferential pathway that can support advective entry as the dominant mode of contaminant entry.

There is an additional consideration that should not be overlooked when conducting a CPM investigation of VI. CPM not only affects the contaminant vapor entry rate into a building, but can also have an impact on air exchange rates within the building being tested. Figure 1.4 shows the effect that CPM had on air exchange rates at the ASU house, where they increased significantly during the testing period. The effect of this is that contaminant expulsion from the house is increased during the testing period, which decreases the indoor contaminant concentration for a given contaminant entry rate. This is a concern voiced in [**holton˙long-term˙2015**][**holton˙long-term˙2015**] an evaluation of the CPM results at the ASU house, and suggested that a tracer-gas test to measure air exchange rate should be conducted during CPM. This is used to introduce a correction term to account for the elevation of air exchange rate above its "natural" values. Since CPM is used to determine the worst-case scenario, this correction term should be used to calculate the indoor contaminant concentration with worst-case entry rates, but "natural" air exchange rate values, i.e. $\approx 0.5\,\mathrm{h}^{-1}$ instead of the elevated values. In this case, it is apparent that the measured values of indoor air concentration might have been a factor of 5 or 6 lower than would otherwise have been obtained for the given change in entry rate. This means that the results in Figure 1.3 might have understated the effect of the entry rate change.

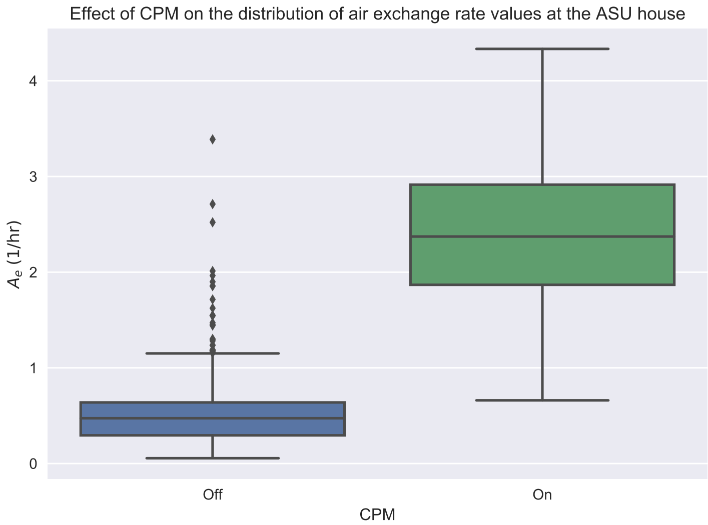


Figure 1.4: Boxplot showing the distribution of air exchange rate values at the ASU house, considering the effect of CPM.

This highlights an issue with CPM at VI sites characterized by diffusive transport. If the increased depressurization doesn't yield higher contaminant entry rates into the building, but elevates air exchange rate, then indoor contaminant concentration may be artificially lowered, and actually underestimate the VI risk. This further shows the advisability of using tracer-gas monitoring to measure air exchange rates when using CPM.

1.3.2 Indicators, Tracers, And Surrogates

As has been discussed throughout this work, VI can be characterized by great temporal variability in indoor air contaminant concentrations. These variations can occur on a variety of time-scales, from days to longer seasonal trends, which can require collection of significant amounts of data to fully characterize. To reduce the resources expended on these efforts, and increase the likelihood of determining the relevant VI risk, it is desirable to employ indicators, tracers, and surrogates (ITS) that can be used to readily predict the periods and conditions when the highest indoor contaminant concentration at a site are likely to manifest. Which specific ITS are most appropriate for this task, and under which circumstances they are reliably employed has, has yet to be determined.

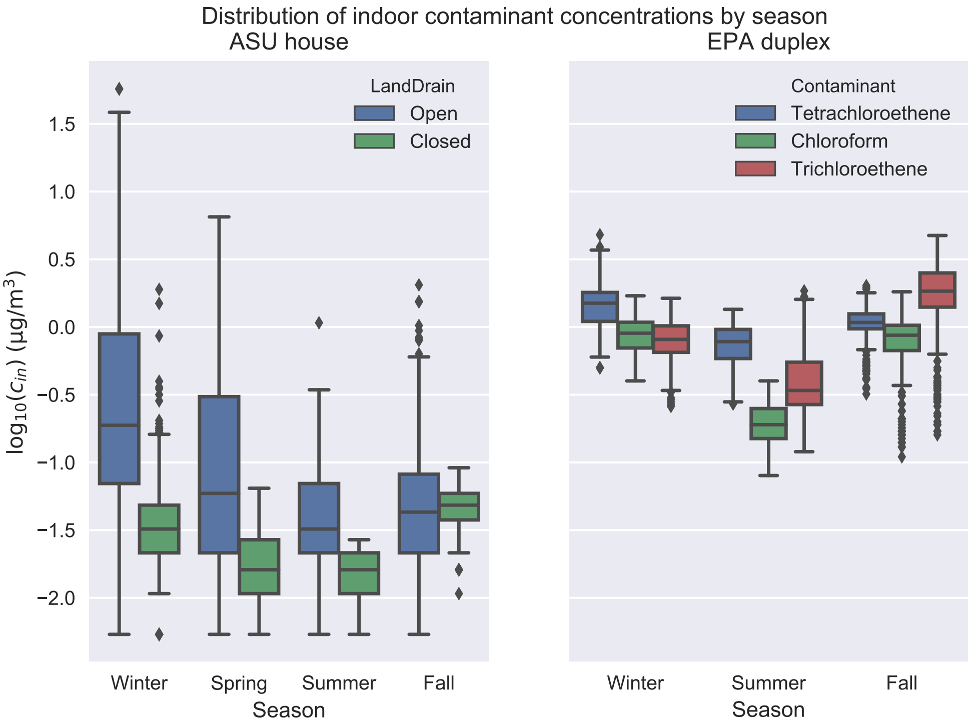


Figure 1.5: Seasonal distribution of indoor contaminant concentration at the ASU house and EPA duplex. At the ASU house, the effect of the land drain preferential pathway is considered. At the EPA duplex, the differences in distribution for three different contaminants are considered. Here "winter" includes December to February, with each subsequent season being defined by the subsequent three months.

Seasonal trends have been to observed to be common at many VI sites, with winter often cited as the period most likely to lead to measurements of elevated indoor contaminant concentrations[**burke˙estimation˙2010**, **hers˙evaluation˙2014**, **miles˙temporal˙2001**, **schumacher˙fluctuation˙2012**, **steck˙indoor˙2004**]. This is a trend that partly occurred at the ASU house as well (see Figure 1.5); indoor contaminant concentrations were indeed highest during winter when the land drain preferential pathway was open. However, this seasonal trend was non-existent after the closing of the land drain. At the EPA duplex, indoor contaminant concentrations were slightly higher during winter and fall than summer, but only marginally so.

The observed seasonal trend at the ASU house when the preferential pathway was open, can be understood by examining the seasonal distribution of indoor/outdoor

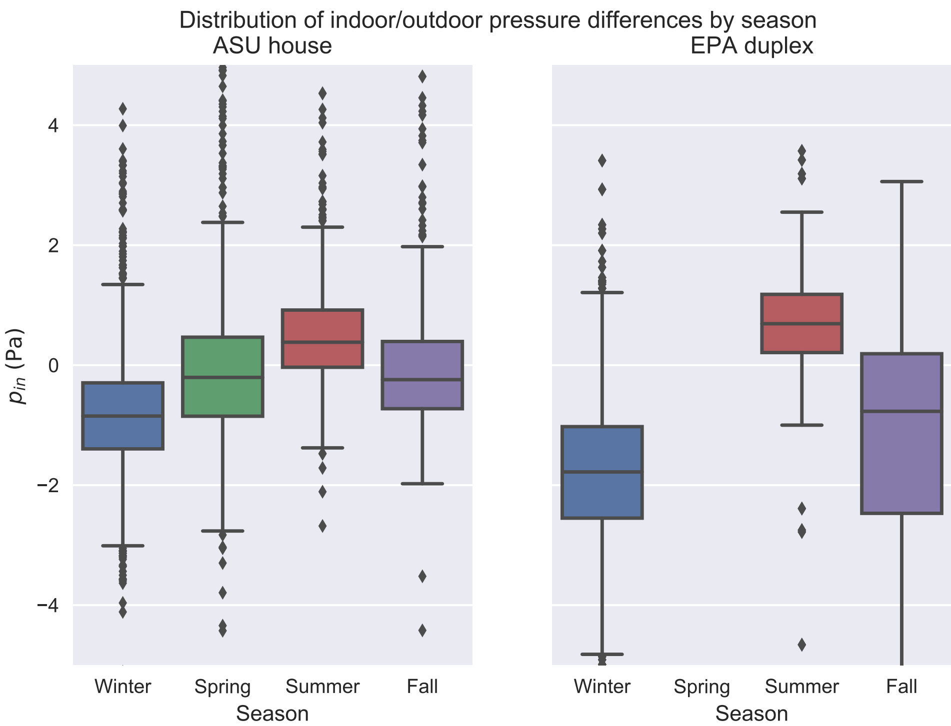


Figure 1.6: Seasonal distribution of indoor contaminant concentration at the ASU house. A negative value indicates that the building is depressurized relative to ambient.

pressure difference, displayed in Figure 1.6. Here we see that building depressurization was greatest during winter, and that the house was slightly less depressurized during the shoulder seasons, and it was usually overpressurized during summer. Considering this together the fact that with advective entry dominated during the period when the preferential pathway was open, explains why indoor contaminant concentrations are higher during the colder seasons. The significant degree of depressurization in winter contributed significantly to what was an advectively determined entry rate during that period of time. The opposite would have been true during summer, when it is likely that the use of air conditioning slightly overpressurized the building. Conversely, when the preferential pathway was closed off, the entry of contaminant shifted to being diffusion rate controlled, and the variations in internal building pressure had little effect on the entry rate.

The EPA duplex exhibited a trend in building pressurization by season that is similar to that observed at the ASU house, i.e. it is more depressurized during colder seasons. This can help explain why indoor contaminant concentrations were likewise slightly higher during colder seasons. While the nature of the contaminant entry into the EPA duplex is not as well understood as that at the ASU house, it was shown in Chapter **??** that the association between building pressurization and indoor contaminant concentrations were somewhere between that of the ASU house before and after the closing of the preferential pathway (compare Figures **??** and **??**). The situation regarding likely entry pathways at the EPA duplex is far more complicated and less well understood than that at the ASU house.

All that can be said at the moment is that while advective contaminant entry may not be dominant at the EPA duplex, it certainly isn't insignificant.

These data and analysis demonstrate that for advection entry controlled sites, building pressurization can probably be used as an effective ITS, whereas at a diffusion entry site, it may not be reliable. The advection entry controlled sites are those built on very permeable soils, or which are influenced by some preferential pathway, which allows advective entry to be the dominant entry pathway. This by itself may be challenging to determine in advance. Even if this could be established, to use building pressurization effectively as an ITS, building pressurization values would need to be known, and instrumenting a house to obtain such values is not generally feasible in VI screening studies. Instead, it would be useful to be able to predict the likely levels of indoor-outdoor pressure difference based on some easier to measure parameters - such as weather conditions.

1.4 Predicting the Extent of Building Pressurization

Building pressurization may be usable as an effective ITS under the right circumstances. However, determining this requires a measurement device to be installed, and moreover this device needs to record values over some length of time to establish trends. Thus, it would be desirable to use some more readily available metric, such as weather data, to predict the degree of building depressurization (since depressurization is of most concernn.in an advective entry scenario).

A variety of factors can contribute to determining overall building pressurization. Some of these are building occupant controlled and induced, such as forced convection associated with heating, ventilation, and air conditioning (HVAC) systems. Patterns associated with these can be difficult to use to for predictive purposes, unless the nature of building operation is regular and predictable. Such HVAC associated effects can at some sites be the dominant factors controlling building pressurization.

Weather primarily contributes to building pressurization through two effects. The temperature difference between the interior of the building produces a density and resultant pressure gradient on either side of a building wall - this is part of what is commonly called the *stack effect* (another part being associated with the withdrawal of combustion air in internally-located heating equipment). Wind striking a building can also produces a pressure effect within the building, the magnitude of which is dependent on wind speed. However, whether some portion of a building is pressurized or depressurized by wind, is complicated and generally depends on the wind direction and building characteristics; wind blowing on a leaky window causes a very different effect compared to wind striking a featureless wall. Equations for predicting building pressurization as a function of weather are available in The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) 2017 Handbook[**american˙society˙of˙heating˙2017˙nodate**] which is used as the primary source in this section.

Weather phenomena can likewise affect air exchange rates, and this has been a significant focus in the VI modeling work by **shirazi˙three-dimensional˙2017**[**shirazi˙three-di**
As their work shows, predicting air exchange rates can be challenging, as accurate characterization generally require detailed knowledge of the interior of a building. This will not be a focus in this work.

The study of the EPA duplex involved continuous monitoring of the indoor and outdoor temperature the wind speed as well as its direction using an on-site weather station mounted on the roof of the building. These data when combined with the recorded indoor/outdoor pressure differences offers an opportunity to establish how well building pressurization can be predicted using weather.

1.4.1 Wind Effects

To truly capture the impact that wind can have on a building and its pressurization, it is usually necessary to conduct wind tunnel tests of scale models of the building, or detailed computational fluid dynamics (CFD) simulations. This is especially true for buildings of even modestly complex geometric shapes, where it is impossible to predict the wind pressure field without these tools. However, it is possible to derive some simple equations to account for wind effects on simple rectangular block-type buildings.

Even with assumptions, the inherent turbulent nature of wind means that it is truly never at steady-state. Thus wind striking a wall generates a distribution of pressures across the surface, that can vary widely in a short period of time; resolving this with a high degree of accuracy requires significant computational effort. However, by considering a time-averaged wind induced pressure field over some period, it is possible to develop simple equations for predicting wind induced pressurization on a rectangular building. The drawback of this approach is that large pressure fluctuations may not be captured.

As the wind strikes the wall of a house, the air velocity in the direction of the wall falls to zero, and the change in momentum in this direction normal to the wall is directly proportional to the pressure on the wall:

$$\Delta p_w = \frac{1}{2}\rho u_{\text{wind}}^2 \tag{1.2}$$

where $\Delta p_w = p_{\text{wall}} - p_{\text{wind}}$ [Pa] is the pressure at the building wall relative to the wind free-stream pressure; ρ_{air} $[\mathrm{kg\,m^{-3}}]$ is the air density; and u_{wind} $[\mathrm{m\,s^{-1}}]$ is the free-stream wind speed, here assumed to be the wind speed measured at some place where it is unaffected by terrain or buildings.

However, (1.2) neglects wind striking the wall at an angle or various obstacles. These can be accounted for by introducing a drag or pressure coefficient C_p into (1.2) giving (1.3).

$$\Delta p_w = C_p \frac{1}{2} \rho u_{\text{wind}}^2 \tag{1.3}$$

C_p is a dimensionless number, varying between -1 and 1, and is a function of wind direction, the building itself, and immediate surrounding area.

Air density ρ changes with temperature and barometric pressure, which can be accounted for via the ideal gas law.

$$\rho = \frac{p_{bar}}{R_{\text{spec}} T} \tag{1.4}$$

here p_{bar} [Pa] is the barometric pressure; $R_{\text{spec}} = 287.058\,\mathrm{J\,kg^{-1}\,K^{-1}}$ is the specific gas constant for dry air; and T [K] is the ambient outside temperature.

To use (1.3) for predicting pressurization at the EPA duplex, we need to choose some C_p value; ideally, a CFD simulation of the structure would be used to determine C_p as a function of the wind direction between 0 and 360 degrees. There are some C_p values available for some generic structures in the American Society of Civil Engineers book for building codes and standards[**simiu˙design˙nodate**]. However, none of these seem applicable to a duplex, nor seem to deal with the building located on the eastern side of the EPA duplex. Instead we assume a generic $C_p = 0.35$, as values in this range are common.

Another factor to consider is that a building will be pressurized or depressurized by wind depending how leaky the wall it strikes is. Generally, walls featuring doors, windows, or other opening will cause a depressurization, while a simple flat wall will cause a overpressurization effect[1]. By inspection of the EPA duplex, we see that

[1] It should be noted that this relationship is not always true, and will depend on the indoor/outdoor temperature difference, as well as the magnitude of the wind speed, as shown by **shirazi˙three-dimensional˙2017**[**shirazi˙three-dimensional˙2017**].

all walls feature windows, but since we're only concerned with the pressurization of the heated side of the duplex (422, the right-hand side half in Figure (??)), we will assume that westerly wind overpressurizes the 422 side.

Wind direction was recorded in degrees relative to northerly wind at the EPA duplex, however, for simplicity we will divide these degrees up into eight cardinal directions (north, north-east, etc) and assign signs to indicate pressurization or depressurization respectively to each direction (see Soil type 1.1).

Cardinal direction	Wind direction [°]	Pressurization sign
N	0 ± 22.5	1
NE	45 ± 22.5	1
E	90 ± 22.5	1
SE	135 ± 22.5	1
S	180 ± 22.5	1
SW	225 ± 22.5	1
W	270 ± 22.5	-1
NW	315 ± 22.5	1

Table 1.1: Division of wind direction into discrete cardinal directions with associated pressurization or depressurization of the heated "right hand side" of the EPA duplex. Here all walls feature windows or doors, except for the western side, which features the other half of the duplex, and hence wind striking from this direction will likely depressurize the heated side.

1.4.2 Temperature Effects

The pressure of any fluid under the influence of gravity varies with elevation and the density of the fluid determines the magnitude of the pressure exerted by a column of fluid. If two columns of air at different temperatures are separated by a wall at, a pressure difference will exist across the wall. Again, this is part of the origin of the *stack effect* in a building.

The pressure of air p as a function of height above some reference plane at height z_0 is given by

$$p = p_0 - \rho g z \tag{1.5}$$

here p_0 [Pa] is air pressure at reference plane z_0 [m]; ρ [$\mathrm{kg\,m^{-1}}$] is the density of air;

$g = 9.82\,\mathrm{m\,s^{-2}}$ is the acceleration due to gravity; and z [m] is the elevation above z_0.

Since we are concerned with predicting the pressure effect for a relatively short building, we can neglect vertical air density gradients giving the horizontal pressure difference as:

$$\Delta p_s = (\rho_{out} - \rho_{in})g(z - z_0) = \rho_{out}\frac{T_{in} - T_{out}}{T_{in}}g(z - z_0) \tag{1.6}$$

Δp_s [Pa] is the portion of the stack effect induced by a horizontal pressure difference; T [K] is the absolute temperature; and the subscripts *in* and *out* are in reference to the indoor and outdoor values respectively. Like in the wind effect section, air density is calculated as function of the barometric pressure and outside temperature.

As a reference height difference $\Delta z = z - z_0$, we use $\Delta z \approx -3\,\mathrm{m}$. This based on the estimated height difference between the EPA duplex basement and some midpoint of the exterior of the building. The recorded indoor/outdoor pressure difference at the EPA duplex is here defined as the pressure difference between wall-port 1 (WP-1), which was on the outside of the house, and the duplex basement.

1.4.3 Air Exchange Rate

It is possible to predict air exchange rate of a building using a similar approach to the one needed for pressure. However, this approach requires detailed knowledge of the leakiness of a building and how different house compartments communicate, and thus is beyond the scope of this work. Even if possible, air exchange rates were not continuously monitored at the EPA duplex, so evaluation of this approaches efficacy using the recorded weather data is difficult. Predicting air exchange rate of a building by modelling was done in the VI modeling of **shirazi˙three-dimensional˙2017**[**shirazi˙three-dimensional˙2017**], where they were able to determine building pressurization and air exchange rates of a building with high accuracy.

1.4.4 Predicting Pressurization At The EPA Duplex

The indoor/outdoor pressure difference p_{in} is assumed to be the sum of the stack effect (Δp_s) and wind contribution (Δp_w), here given simply by p_s and p_w respectively.

$$p_{in} = p_s + p_w \tag{1.7}$$

Figure 1.7 shows the recorded indoor/outdoor temperature difference and wind speed, how these two contribute individually to p_{in}, and how they contribute together to p_{in} across the EPA duplex study period.

Figure 1.7 shows that with this relatively simple approach, the general trend of p_{in} is captured. Major errors seem to be mostly due to either a failure to capture large changes in p_{in}, or overpredict changes in p_{in}. Both of these seem to stem from a relatively poor characterization of the wind influence, which seems strongly correlated with large changes in p_{in} in general.

The differences and individual contributions of the temperature and wind effects can be further examined in Figure 1.8 and Table 1.2. These show that this approach reasonably predicts most of the p_{in} distribution, specifically the mean pressurization and standard deviation are captured, but fails to capture, the important outliers where the building is significantly depressurized. This is perhaps due to poor accounting for the wind effect, and with more advanced modeling of the influence of wind, such in the work by **shirazi˙three-dimensional˙2017**[**shirazi˙three-dimensional˙2017**], this is likely to be better captured.

		Predictions	
	Data	p_s	$p_s + p_w$
Mean	-1.33	-1.50	-1.31
Std.	2.15	1.12	1.96

Table 1.2: Mean and standard deviation of recorded and predicted building pressurization. Here considering the temperature induced stack effect pressure difference p_s alone, and the combined contribution of wind induced pressure difference p_w and p_s.

Regardless, this approach shows that using temperature, wind, barometric pres-

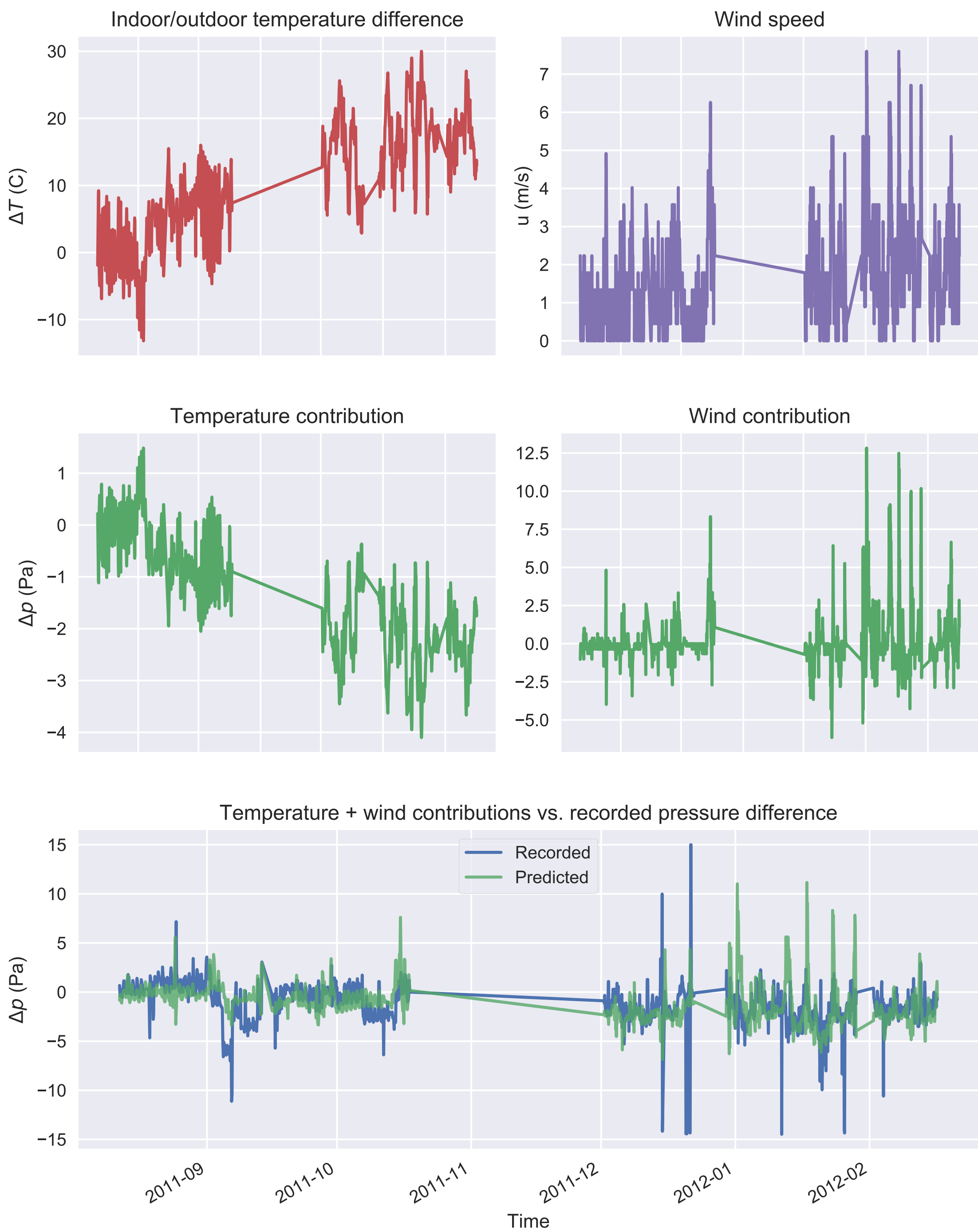


Figure 1.7: How indoor/outdoor temperature difference ΔT and wind contributes to building pressurization at the EPA duplex. The top left panel shows $\Delta T = T_{in} - T_{out}$, i.e. a positive value indicates that it is warmer indoors than outdoors. The top right shows the wind speed u_{wind}. The middle panels shows the contributions of ΔT and u_{wind} to p_{in} respectively. The bottom panel shows the combined contribution of ΔT and u_{wind} to p_{in}, and compared to the recorded p_{in} values. $p_{in} < 0$ indicates that the building is depressurized.

sure, and some simple assumptions about a building, it is possible to reasonably accurately characterize how building pressurization may change in the long-term

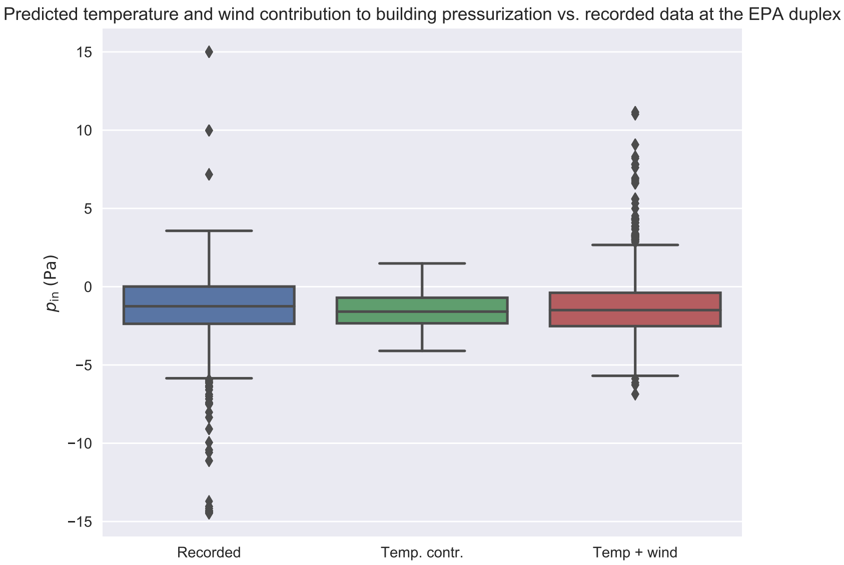


Figure 1.8: Boxplot comparing the predicted p_{in} to the recorded values, and how the temperature and wind components contributes to the distribution of values.

and short-term. This is particularly useful for planning when to conduct testing at sites that can be identified as more advection entry dominated; at such a site samples should logically be collected when the building is most continuously depressurized, i.e. when $\Delta T > 5\,°\mathrm{C}$ and when there is little wind so as to reduce uncertainty from its influence. As Figure 1.8 emphasizes, the main contribution to the depressurization is the stack effect, which is most severe in winter. Thus, these results point in the direction of supporting the rule of thumb that sampling should be done in the cold months, in order to get the most conservative values. As noted before, this really applies mostly to sites at which advective contaminant entry dominates.