Quantifying exchange processes in the urban canopy layers of dense neighborhoods

by
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Abstract

There is a global trend towards urbanization, particularly in developing regions that are home to new and rapidly growing cities. In the center of large, dense urban areas, weak exchange between the urban canopy layer (UCL) and the urban boundary layer (UBL) above it results in insufficient removal of heat and pollutants. The magnitude of the exchange processes between the UCL and the UBL is directly related to the built environment that is devised by urban designers and influenced by policy makers. In this work, representative urban forms are defined and the vertical mixing potential is quantified for each case using computational fluid dynamics (CFD). Insight is gained into the flow phenomena responsible for these results and the findings are presented in the context of urban design.

Dense, repetitive, orthogonally-gridded neighborhood layouts are common in urban areas and are selected as the subject of analysis. Using dimensional reasoning, the relevant geometric parameters, including the dimensions of the city block as well as the spacing between blocks, are determined. These quantities are parametrically varied and the resulting flow fields are calculated using CFD for each case. Next, simulated passive scalars are released into each neighborhood from a near-ground volumetric source, and the average steady state non-dimensional concentrations are calculated in the UCL and at pedestrian height. Using these concentrations as metrics, the vertical mixing potential is quantified as a function of each of these building geometry parameters. Transient results, fluid mechanical reasoning and flow visualizations are used to develop a physical understanding of the flow phenomena responsible for these quantitative results allowing them to be interpolated and extrapolated with confidence. Analytical models are developed where applicable. The results are presented at both a neighborhood scale, of interest to policy makers and urban planners, and at a street canyon scale, of interest to urban designers and architects. In addition to the repetitive neighborhood, common urban planning elements are evaluated to determine how changes in these forms affect mixing within the UCL and between the
UCL and the UBL. These include variations in building height, the introduction of parks or open areas to a gridded neighborhood and building clustering.

In gridded neighborhoods with buildings of uniform height and one grid axis aligned with the wind, street canyons perpendicular to the wind have larger vertical mixing potentials than street canyons aligned with the wind. Decreasing street canyon aspect ratios significantly increases the vertical mixing potential in these gridded neighborhoods. Introducing height variation to a neighborhood with uniform height buildings increases the vertical mixing potential at a neighborhood scale and reduces the difference in vertical mixing potential between the street canyons perpendicular to and aligned with the wind. The addition of parks and open areas also increases the vertical mixing potential in gridded neighborhoods. Finally, preliminary work on building clustering suggests these urban forms have greater vertical mixing potentials than gridded neighborhoods, in general.

Guidelines and quantitative methods are developed for practitioners to use in the assessment of the impact of a neighborhood scale design on the exchange processes between the UCL and the UBL, information that might otherwise be inaccessible or cost prohibitive. Examples that show how to apply these methods are presented throughout this work, and the implications of urban design choices on pedestrians are discussed. A supplemental summary of the most relevant findings for practitioners is also provided.

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Chapter 1

Introduction and motivation

This work is motivated by a global trend towards urbanism, specifically in regions classified as “less developed” by the United Nations [2012]. The Population Division of the United Nations Department of Economic and Social Affairs classifies all regions of Africa, Asia (excluding Japan), Latin America, the Caribbean, as well as Melanesia, Micronesia and Polynesia to be “less developed” for statistical purposes. These regions are home to new and growing cities, and this growth in urban population is predicted to continue through the coming decades as shown in Figure 1-1. Large scale urbanization could be seen as a major problem to be cope with in the next century; alternatively, it can be viewed as a unique opportunity to find solutions that can have a positive impact at a global scale.

One example of this sort of urbanization is the island nation of Singapore, which has undergone rapid urban development in the past 50 years. This development has led to changes in the island’s microclimate. Specifically there have been measurable differences in the nighttime air temperature, which can be attributed to the urban heat island (UHI) phenomenon [Chow and Roth, 2006]. The interface between the urban canopy layer (UCL) and the urban boundary layer (UBL) is the surface defined by the height of the building rooftops, shown schematically in Figure 1-2 [Oke, 1987]. As the island becomes more populated, there will continue to be pollutants, for example vehicle emissions, released into the heavily populated UCL and retained there unless
removed into the UBL. Insufficient removal of heat and pollutants is a result of weak exchange between the UCL and the UBL, and this can be directly attributed to building geometry, neighborhood layout and atmospheric conditions.

![Population vs. Year, global urbanization predictions](image)

Figure 1-1: Population vs. Year, global urbanization predictions for more developed and less developed countries [United Nations, 2012]

Neighborhood layout and building geometry are devised by urban designers and influenced by policy makers; however it is not common practice to consider airflow in a comprehensive way during the design process. This is especially true in the early design process, the stage when many of the major morphological design decisions take place.

Section 1.1 introduces the urban heat island phenomenon, discusses why it is detrimental in urban areas, and presents the concept of mitigating the phenomenon through urban design. Section 1.2 asserts that urban air quality is affected by the geometry of urban areas, and argues that air quality should be considered in the early design phase of neighborhoods. Section 1.3 discusses the need for urban designers and
policy makers to have quantitative methods for assessing the impact of a neighborhood scale design on urban microclimate, states the goals of this thesis and presents the layout for how they are addressed.

1.1 The urban heat island phenomenon

Based on measurements taken in London and surrounding areas, Howard [1833] concluded that “the temperature of the city is not to be considered as that of the climate; it partakes too much of an artificial warmth, induced by its structure, by a crowded population, and the consumption of great quantities of fuel in fires.” He observed that in London these differences were on average $3.7^\circ F$ at night and about $0.3^\circ F$ during the day. The trends that he discovered in the data are now recognized as the UHI phenomenon, defined as a variation in air temperature between the countryside and an urban area [Oke, 1987]. The UHI intensity, $\Delta T_{u-r}$ is defined as the difference between the maximum temperature in an urban area at a given time and a background rural temperature at the same time, as shown in Figure 1-3 [Oke, 1987]. As Howard [1833] noted, and as it is now widely accepted, the UHI intensity is greater at night [Oke, 1987; Stull, 1988; Chow and Roth, 2006].

Observations of urban areas with a population of approximately $10^3$ exhibit maximum UHI intensities, $\Delta T_{u-r(max)}$, of $2 - 3^\circ C$, while $\Delta T_{u-r(max)}$ can equal $8 - 12^\circ C$
in urban areas with populations of more than $10^6$ as shown in Figure 1-4 [Oke, 1982; Stull, 1988].

These observations are particularly alarming because by 2025 47% of the global urban population will be in cities of $10^6$ or more inhabitants, up from 40% in 2011, with cities with populations of at least $10^7$, known as megacities, undergoing the largest percentage increase [United Nations, 2012]. As of 2011 there were 23 cities with populations of at least $10^7$, and 6 of these cities are in equatorial climates [United Nations, 2012; Kottek et al., 2006]. By 2025 it is projected that there will be 37 cities with populations of at least $10^7$, consisting of 12 cities in equatorial climates. All of the cities in equatorial climates are considered to be in developing nations by United Nations [2012], which means that on average they are projected to grow in population faster than more developed regions. Equatorial climates undergo little variation in average daily temperature year-round, and the only respite from the heat for the population is the diurnal variation in temperature. If $\Delta T_{u-r}(\text{max}) = O(10^\circ\text{C})$ in these megacities, millions of people will be affected. These effects include increased discomfort among pedestrians, increased energy use by cooling systems and possible heat-related health risks.

Causes of the UHI phenomenon include an increase in short wave radiation absorption by urban surfaces relative to rural surfaces during the day due to increased
Figure 1-4: $\Delta T_{u-r(max)}$ vs. Population for North American and European cities [Oke, 1982]

...
1.2 Urban air quality

Vehicles are a large source of pollution in regions of North America that are not highly industrialized [Oke, 1987]. In dense urban areas with traffic, these sources can be simplified as a city-wide near-ground area or volume source [Oke, 1987]. The particles from these sources remain in the UCL until they are advected out of the city laterally or vertically transported to the UBL. It is important to understand the role of building geometry in enhancing or weakening the transport and dispersion of these emissions so that urban air quality may be considered by urban designers in the design phase.

Aside from urban design, gaining an understanding of the flow phenomena responsible for transporting emissions in urban settings would be useful to inform first responders about the affected area during an accidental or intentional chemical release in a heavily populated area [Britter and Hanna, 2003]. Helpful information would include estimates of the affected area, and the time constant associated with vertically removing the particles.

1.3 The role of urban designers and policy makers

Urban designers need simple guidelines to inform early-phase design decisions that affect neighborhood microclimate [Eliasson, 2000; Brown, 2003]. Existing techniques to study airflow through a neighborhood and its effect on the urban microclimate are either too slow or require too much technical expertise to be suitable for early-phase studies performed by urban designers. An appropriate set of design guidelines would quickly provide users with relevant outputs without substantially influencing their existing design process [Brown, 2003]. Rules of thumb with quantitative outputs would be ideal for comparing different neighborhoods or a series of design iterations or alternatives.
To this end, the work in this thesis aims to (1) quantitatively compare the vertical mixing potential of common urban forms as their geometries are parametrically varied, (2) gain a physical understanding of the flow phenomena responsible for these quantitative results using fluid mechanics and (3) summarize these results so they may be used by urban designers and policy makers to inform early phase urban designs and zoning policy.

Chapter 2 discusses existing techniques for assessing and quantifying airflow, dispersion or transport in urban areas, and assesses which approach would be useful in fulfilling the above-stated goals. Chapter 3 explains the approach taken in this thesis for quantitatively comparing different neighborhood-scale building geometries, asserts at what scale this data should be presented to urban designers and policy makers and restates the goals of this thesis in the context of the selected approach. Chapter 4 focuses on dimensional analysis techniques that are used throughout this work to broaden the results to different atmospheric and source conditions. Different aspects of gridded building geometries are studied parametrically to assess their ability to mix scalars from the UCL to the UBL in Chapters 5–7, and where possible the flow phenomena are explained using fluid mechanics and physical reasoning. Case studies focusing on the influence of large and small open areas and building clusters on average concentrations at a neighborhood scale are discussed in Chapter 8. This work is summarized and presented concisely to a policy and urban design-oriented audience in Chapter 9. This chapter includes examples as well as a discussion of limitations. Finally, conclusions and future work are presented in Chapter 10.
Chapter 2

Review of existing methodologies

There are existing methods to quantify the airflow and mixing in the UCL, however none of these methods alone is suitable for meeting all of the goals of this thesis. Section 2.1 discusses experimental studies and empirical models based on experiment. Section 2.2 describes various types of computational fluid dynamics (CFD) and case studies performed using these techniques. Section 2.3 explains parametric studies performed using previously discussed experimental or CFD techniques. Section 2.4 describes analytical approaches based on the conservation equations and simplifying assumptions. Section 2.5 presents the approach used in this thesis, a physics-based approach, which involves comprehensive parametric studies supported by inspection and analysis of the flow fields. This approach will lead to interpretations of the trends in the results based on a fluid mechanical understanding of the roles of the relevant flow phenomena.

2.1 Experimental studies

Experimental investigations in and around urban areas are important because they result in data sets that can be used to evaluate simulations, analytical or empirical models and one’s qualitative understanding of the phenomena observed in the UCL or UBL. Studies where measurements were taken in the field are discussed in Section
2.1.1 Section 2.1.2 describes experiments where measurements were taken in a wind tunnel. Examples of empirical models based on field or wind tunnel data are presented in Section 2.1.3.

2.1.1 Field experiments

Data measured in urban areas such as pollutant concentrations, wind velocities, turbulent fluxes and temperatures is vital to quantifying air quality and pedestrian comfort. Because the geometry of urban areas is complex, analytical solutions to the Navier-Stokes equations are impossible. Scientists interested in these problems often resort to CFD or simple analytical or empirical models to estimate how momentum, species and heat are transported around buildings. Field data allows for direct, in-situ measurements of these quantities, which is necessary for evaluating indirect approaches.

The Joint Urban 2003 field study, centered in the Central Business District (CBD) of Oklahoma City, involved gathering data over the course of 34 days using hundreds of sensors including 142 3-D sonic anemometers [Allwine et al., 2004]. In addition to taking meteorological measurements of the city, sulfur hexafluoride was released from one of three locations in the CBD during 10 8-hour intensive operation periods. Though many measurements were taken within a few blocks of the release areas, some sensors were located as far as 6 kilometers from the CBD. There were more than 20 organizations involved in this effort. They measured wind and turbulence levels in 3-D from the ground to several kilometers above the ground. They also measured concentrations in the UCL downwind of the sulfur hexafluoride releases as well as inside buildings downwind of the releases. This wealth of data is public and has been used to evaluate transport, dispersion and CFD models [Warner et al., 2007; Neophytou et al., 2011].

The Dispersion of Air Pollution and its Penetration into the Local Environment (DAPPLE) project was conducted at the intersection of Marylebone Road and Gloucester Place in Westminster, Central London, England [Arnold et al., 2004; Robins, 2013]. This intersection was chosen because intersections are less studied
than idealized two-dimensional street canyons and they are more realistic than a two-dimensional street canyon in an urban setting [Arnold et al., 2004]. Six organizations were involved in this effort. This project consisted of five field campaigns over the course of 2003-2008, and the radius of the study area was approximately 250 m. Though the study utilized an order of magnitude fewer sensors than the Joint Urban 2003 field study, the DAPPLE experiment conducted wind tunnel, numerical and analytical studies in parallel with the experimental work. The experimental data from this work is available from the scientists involved upon request as is all of the analytical and empirical work conducted during the study [Robins, 2013]. This data has been used to assess simple analytical models that predict flow and dispersion in intersections as well as empirical models developed based on measurements from other field experiment campaigns [Dobre et al., 2005; Neophytou and Britter, 2004a,b,c].

Field data is invaluable for both computational and empirical model evaluation. It is less useful for model development because the experiments are not repeatable due to continually changing meteorological conditions. Additionally, one must be careful when drawing general conclusions from the data because results may be specific to the building geometry or climate of the field experiment. Isolating the effect of building geometry in a real world setting would be difficult because of confounding anthropogenic factors such as vehicle-induced turbulence and waste heat from heating, ventilation and air-conditioning systems. Because of the number of organizations involved in these campaigns, as well as the cost of sensors and the time and care needed to deploy and monitor them, it would be prohibitively expensive and time-intensive to gather field data for enough cases to determine how specific building geometry parameters affect mixing processes between the UCL and the UBL.

### 2.1.2 Wind tunnel experiments

Wind-tunnel experiments can be used to resolve the wind and turbulence field above and around a specific urban geometry [Schatzmann et al., 1998]. They can also be used to study the effect of changing one parameter of the incident flow over a specific geometry (e.g. wind speed, wind direction, turbulence levels) because unlike
field experiments, the inlet conditions can be directly specified. Additionally, they may be used to develop new turbulence closure schemes for CFD models, evaluate assumptions of simple analytical models and generate new empirical models based on experimental data sets. Wind-tunnel experiments can quantify uncertainty in field experiment data sets because wind tunnel experiments are repeatable [Schatzmann et al., 1998]. Wind tunnel experiments are frequently used to study various aspects of the flow field in urban areas, a review of this work has been carried out by Kanda [2006]. Ahmad et al. [2005] wrote another review, focusing on wind tunnel studies at a street canyon scale. The examples discussed below are representative of work at a neighborhood scale and a street canyon scale, by Kastner-Klein and Rotach [2004] and Hang et al. [2010a], respectively.

Kastner-Klein and Rotach [2004] built a 1:200 model of buildings representing a section of the central part of Nantes, France, 400 m-diameter. Vertical profiles of horizontal wind velocity, turbulent shear stress and turbulent kinetic energy were measured at points throughout the model of the city. This data was used to verify and improve upon relationships between a parameterization of building geometry (plan area index) and the parameters found in the similarity theory-based logarithmic law for the mean vertical profile of the horizontal wind above a rough surface (displacement height and roughness height) [Stull, 1988; Kastner-Klein and Rotach, 2004]. Kastner-Klein and Rotach [2004] also used the wind tunnel data to develop an expression that fits their data better than the logarithmic law for the vertical profile of the horizontal wind, spanning from the ground to the height in the flow that is horizontally homogeneous.

Hang et al. [2010a] measured the three components of velocity as well as the turbulence intensity along models of long, narrow, idealized street canyons of four different aspect ratios in a wind tunnel. They used this data to evaluate CFD results calculated with both the $k - \epsilon$ and the Renormalization Group $k - \epsilon$ turbulence models. They found that both models predicted the velocity profiles well, however both models under-predicted the turbulence intensity below roof level. Both CFD models were able to capture the dominant mean flow mechanisms upwind, downwind
and along the street canyons and were therefore used to calculate the air change rate per hour as a means of quantifying the ventilation in a variety of street canyon cases. Using this information, they drew conclusions about urban design in Hong Kong. This data was also used to evaluate the validity of the CFD simulations in Hall [2010].

Wind tunnel data is important for the development and evaluation of empirical models, as well as for assessing CFD simulations. It would be prohibitively expensive and time-intensive, however, to gather enough wind tunnel data to physically understand why specific aspects of urban form contribute to exchange between the UCL and the UBL. Additionally, data from a wind tunnel study is not readily interpreted by urban designers as a means to inform the design process.

2.1.3 Empirical models based on experimental results

Empirical models based purely on experimental results are useful for condensing a large amount of experimental data into a function that relates two or more parameters of the experiment. These models may be useful for interpolating, or cautiously extrapolating the directly measured data to predict information about an urban geometry that has not been studied by experiment.

Macdonald et al. [1998] presented empirically derived models developed by various researchers that relate the plan area density (ratio of the plan area of obstacles to the total lot area) and the frontal area density (ratio of the frontal area of obstacles to the total lot area) to the roughness height and displacement height found in the similarity theory-based logarithmic law used to predict the vertical profile of the horizontal wind above urban areas.

Kubota et al. [2008] performed an impressive 352 wind tunnel experiments, studying 22 270x270 m sections of Japanese cities over 16 wind directions to determine the relationship between the plan area density and the average velocity of the wind at pedestrian height. They fit the velocity data for city sections characterized by detached homes with a linear model, and used a separate linear model to fit the velocity data for city sections characterized by taller apartment complexes. Because the phys-
Empirical reasons for the trends in their results are not explained, and the cases are limited to Japanese cities, the work may not be applicable to other urban areas.

Empirical models based on experimental data can be useful for urban designers and policy makers to understand experimental data more easily than a presentation of the raw data. Without a physical understanding of the results at the street canyon-scale or a careful study systematically varying one parameter of urban geometry while holding all others constant, however, one cannot be sure that these models are robust for use in interpolating or extrapolating to other urban areas.

2.2 Computational fluid dynamics-based case studies

Airflow around urban geometry is turbulent and complex, thus it cannot be resolved using a direct application of analytical methods. Numerical methods, specifically CFD, are increasingly being used in the field of urban climatology to resolve flow fields at the street canyon or neighborhood scale. This technique involves discretizing the conservation equations and solving them at points defined by a grid or mesh that divides up the computational domain. Section 2.2.1 explains the implications of direct numerical simulation of these equations. Section 2.2.2 describes large eddy simulation, a method of filtering the conservation equations to make them easier and faster to computationally solve. Case studies using large eddy simulation with outputs that are relevant to urban designers are also presented. Section 2.2.3 discusses a simplification of the equations based on time-averaging known as the Reynolds-averaged Navier-Stokes equations. Examples of case studies using Reynolds-averaged Navier-Stokes equations with urban-design related outputs are also presented.

2.2.1 Direct numerical simulations

Direct numerical simulation (DNS) is the most accurate way to solve the Navier-Stokes equations for a turbulent flow field because all of the fluid motions are resolved...
To resolve all fluid motions, however, the mesh must be able to resolve (and thus be smaller than) the Kolmogorov scale, \( \eta \), associated with the dissipation of kinetic energy. The Kolmogorov scale is defined as:

\[
\eta = \left( \frac{\nu^3}{\epsilon} \right)^{\frac{1}{4}}
\]

where \( \nu \) is the kinematic viscosity of air and \( \epsilon \) is the rate of dissipation of turbulent kinetic energy [Tennekes and Lumley, 1972]. \( \epsilon \) is estimated as

\[
\epsilon \sim \frac{u^3}{l}
\]

where \( u \) is the characteristic velocity of the large scale motion and \( l \) is integral length scale, which Ferziger and Perić [2002] defines as “the distance over which the fluctuating component of the velocity remains correlated,” often taken as the size of the largest turbulent eddy based on a characteristic length of the object being simulated.

The domain must be larger than the integral length scale, which means that for a three-dimensional simulation the number of grid points must be at least \( \left( \frac{l}{\eta} \right)^3 \). Consider a street canyon scale simulation with an integral length scale of 10 m and with air flowing over it at 1 m/s. \( \nu \) is on the order of \( 1 \cdot 10^{-5} \, \text{m}^2/\text{s} \) for air. The Kolmogorov scale is \( \approx 3.2 \cdot 10^{-4} \, \text{m} \), and the minimum number of grid points required to use DNS is \( \approx 3.2 \cdot 10^{13} \). This number of grid points unreasonable for most computers today, however this domain is only a single street canyon. Consider a neighborhood-scale domain with an integral length scale of 200 m and an incident wind speed of 5 m/s. The Kolmogorov scale in this case is \( \approx 2 \cdot 10^{-4} \, \text{m} \) and the minimum number of grid points required to simulate this domain in three dimensions is \( \approx 1 \cdot 10^{18} \), which is too large of a mesh to simulate on todays computers. For reference, this mesh is eleven orders of magnitude larger than any simulation performed in this thesis. DNS is too computationally expensive to simulate airflow around a group of buildings. DNS is also completely unfeasible to use in a parametric study or during the design phase to evaluate the airflow around different iterations of a design. If the computational
power were readily available, DNS outputs would be useful to gain a qualitative understanding of the flow field in a small domain using flow visualization or to evaluate the less accurate turbulence models, such as those discussed in Sections 2.2.2 and 2.2.3. The raw outputs of a DNS simulation, transient velocity data at a very fine scale, would not be useful to guide urban designers attempting to design with vertical mixing in mind.

### 2.2.2 Large eddy simulations

Large eddy simulation (LES) approximates turbulent flow by calculating the large-scale, more energetic eddies more accurately than the smaller eddies because the large eddies are responsible for most of the transport of conserved properties [Ferziger and Perić, 2002]. In an LES model, the Navier-Stokes equations are filtered, leaving only the large-scale terms, and the small-scale eddies are included in the form of a sub-grid-scale Reynolds stress, which may be approximated in various ways as summarized in Ferziger and Perić [2002].

Gallagher et al. [2012] used LES techniques to study the effect of passive controls, specifically one or more 0.5 m low boundary walls (LBWs), on pollutant concentration at pedestrian breathing height along footpaths. Various asymmetric street canyons oriented perpendicular to the wind were considered. They simulated two LBW configurations in three different canyon shapes at two different wind speeds. Concentrations were monitored at 1.0 m and 1.76 m, the breathing height of children and adults, respectively. These results were compared to control cases with no LBWs. The impacts of the LBW configurations on the vortical flow patterns were discussed briefly, and these were used to explain the physics behind the differences in concentration between the control cases and the LBW cases. They did not find an LBW position resulting in concentration reductions along all footpaths for all cases, but their results proved that LBWs can have a measurable effect on concentration levels in street canyons perpendicular to the wind. Because the concentrations were monitored at adult and children breathing heights, the design implications of the results of this case study are able to be understood by urban designers. The results
can be used to inform decisions about LBW placement in asymmetric street canyons perpendicular to the wind.

Gu et al. [2011] simulated flow fields in one uniform street canyon and three non-uniform street canyons oriented perpendicular to the wind using LES techniques. The non-uniform canyons each had a different percentage of tall buildings comprising some of both the windward and leeward walls, ranging from 25% to 75% in increments of 25%. The control case was a standard uniform street canyon, which measured 30 m in width and H1=30 m in height. The leeward and windward walls of the non-uniform cases were split into H1=30 m and H2=45 m tall sections, and the windward and leeward 45 m-high sections were always positioned diagonally from one another, as shown in Figure 2-1. They simulated the release of pollutants from a line source located at the center of each canyon. The flow structures and how they contributed to or inhibited pollutant transport out of the street canyons were discussed in detail for each case. They presented mean and maximum concentration values for each case at pedestrian height, and found the 25% tall-building configuration yielded the lowest mean and maximum concentrations. These results could be used by an urban designer to inform the design of a non-uniform street canyon aligned perpendicular to the wind. Because a physical reason for the trend in concentration data as it varies with the percentage of tall buildings was not discussed, conclusions drawn from this work should not be interpolated to other values of tall building percentage.

Figure 2-1: Four cases of building street layouts [Gu et al., 2011]
Both Gallagher et al. [2012] and Gu et al. [2011] used LES to gain a physical understanding of flow phenomena for particular urban-like geometries, and presented their results in the context of urban design implications, thereby meeting the second and third goals of this thesis for the geometry of their case studies. These geometries were very idealized, however, and lacked much of the three-dimensionality of urban areas which makes flow fields complicated, such as intersections and changes in wind orientation. Additionally, perhaps due to the computational expense of LES, their domains were limited in size and number, making a truly parametric study of their cases infeasible. For example, varying the aspect ratio of the idealized street canyon in both of these cases may significantly change their results and the conclusions drawn from them. Gallagher et al. [2012] focused on the effect of combinations of parameters on concentration, rather than focusing on the effect of any one parameter. Gu et al. [2011] treated their study like four distinct cases rather than a study of the effect on concentration of changing the percentage of tall buildings in a non-uniform street canyon, parametrically. These limitations restrict the real-world applicability of their results to very specific cases.

Overall, LES is less computationally expensive than DNS, and it may be used at higher Re. It is useful for evaluating less-accurate computation techniques such as those discussed in Section 2.2.3 or for engineering applications where transient flow visualization and accuracy is important. It is less accurate than DNS, however, and it is still too computationally expensive to be used as a design-process tool. Like DNS, the fine-scale and transient raw outputs of a simulation using LES would not be useful to an urban designer. LES results from case studies with urban design applications must applied with caution, only to geometries similar to those studied.

### 2.2.3 Reynolds-averaged Navier-Stokes

Reynolds averaging techniques may be used to remove the unsteadiness from the Navier-Stokes equations, resulting in simpler equations known as the Reynolds-averaged Navier-Stokes (RANS) equations. These RANS equations contain terms that must be approximated with turbulence models to close the set of equations [Ferziger and
Turbulence closure schemes are discussed in Ferziger and Perić [2002] and include $k$-$\epsilon$ and Reynolds stress model schemes which require solving two and seven additional partial differential equations, respectively.

Huang et al. [2009] investigated the effect of wedged-shaped roofs on pollutant transport in two-dimensional street canyons oriented perpendicular to the incident wind using the RANS equations. They considered three types of buildings: a rectangular (flat-roof) building, a wedge-roofed building where the lower edge is the same height as the rectangular building (tall, wedged-roof) and a wedge-roofed building where the upper edge is the same height as the rectangular building (short, wedged-roof). They simulated the flow field around 17 street canyon configurations, i.e. every combination and orientation (relative to the wind) of two buildings from this set, except the combinations with both a tall wedged-roof building and a short wedged-roof building. A $k$-$\epsilon$ turbulence closure scheme was used. A line source with a constant emission rate of an ethane and air mixture was placed in the center of each street canyon and the concentration fields were calculated for each case. They found that the roof configuration had a strong influence on the vortex structure and pollutant dispersion within the street canyons. Specifically, they found that canyons with a taller leeward wall than windward wall or walls of equal height were better at removing pollutants than those cases where the leeward wall is shorter than the windward wall. They also found that scenarios with larger horizontal velocity near the ground had lower concentrations at pedestrian level, and they discussed which roof configurations led to greater near-ground horizontal velocities. Their results could be used to inform the roof design of a building along a street canyon which is perpendicular to the dominant wind direction.

Lateb et al. [2010] simulated the flow field around two neighboring buildings which were modeled after real-world buildings in Montréal. One building is in the wake of the other building for the prescribed incident flow field. The downwind, shorter building had a smoke stack on its roof which acted as an pollutant emission source. They calculated the flow field with the RANS equations and used a $k$-$\epsilon$ turbulence closure scheme. Results were computed for two different stack heights, each with two
different pollutant exhaust velocities. Concentration data was monitored at various
heights on the leeward side of the upwind building, and along the roof of the downwind
building near the emission stack. The results were compared to wind tunnel and field
experiment data, and they discussed where in the flow field the $k$-$\epsilon$ scheme performed
well, and where there were large discrepancies between the measured and calculated
data. Specifically, they noted that the wake zone observed behind the tall building in
the experiments were not captured in the experiments, however the street canyon zone
between the two buildings was well reproduced. They noted that the leeward wall of
the downwind building would be the best location for fresh air intakes to be used by
the mechanical systems of the building, an insight that would have been useful in the
design phase. Additionally, the data taken at various heights just outside the upwind
building for this incident wind profile could have been used by designers to assess the
concentrations entering the building at each story when using natural ventilation.

Huang et al. [2009] and Lateb et al. [2010] used RANS equations to discover
complex flow phenomena around particular geometries and discussed how these phe­
nomena affected concentration levels. They each presented their results in a way that
to some extent would be useful to urban designers, which means that they met the
second and third goals of this thesis. Both of these groups focused on very specific
and idealized cases, however, which would not be easily applied to realistic situations
or situations with differences in geometry to those studied. Because the $k$-$\epsilon$ scheme
is computationally inexpensive, the study by Huang et al. [2009] would have been
improved by parametrically varying the aspect ratio of the two-dimensional street
canyon so that the work could be applied to more than just a few cases.

In general, RANS simulations are less computationally expensive than LES sim­
ulations, and they produce fewer outputs. These two features make RANS models
useful for engineering applications where the flow field is only being simulated to
compute the value of a few quantitative outputs. RANS equations are fast enough to
be used to simulate various iterations of a particular design, and are implemented in
many commercial CFD software packages.
Using these codes requires a technical background in fluid mechanics, which is uncommon in urban designers. This means that running CFD code for each design iteration during the early design process would require working closely with an engineer. This would result in an increase in the cost of the project, thereby negatively influencing the existing design process, which is unacceptable as an industry-wide practice [Brown, 2003]. It does have potential as a tool used for performing parametric studies by engineers to derive design guidelines for urban designers, however, which is discussed in Section 2.3.

2.3 Parametric studies

Parametric studies isolate the quantitative effect of a particular independent parameter on other dependent parameters by systematically varying the independent parameter in each simulation or experiment. The results are often summarized in the form of a graph to visualize the influence of the independent parameter on the output of interest. A graphic visualization of this sort of information would be understandable to an urban designer or policy maker and could lead to the development of design guidelines for designing with the relevant dependent parameter in mind.

Reiter [2010] created simple graphics to explain how the wind speed at pedestrian level near a single building is affected by the geometric parameters of the building. The graphics are quantitative and are based on systematically varying the geometry of the building, and simulating the flow around it with the RANS equations and a $k-\varepsilon$ turbulence closure scheme. The purpose of his graphics is to help the user design a building without exceeding the maximum wind speed allowable for pedestrian comfort. He quantified qualitatively well understood airflow phenomena near buildings such as the corner effect and the front vortex for various building heights. He carefully noted for what scenarios his calculations are relevant, and at what values of building parameters his graphics are no longer applicable. He also began to investigate the effects of more realistic urban scenarios, such as a tall building among a grid of short buildings, on pedestrian level airflow; however this work is less comprehensive.
Bady et al. [2008] conducted a parametric study using the RANS equations and a $k$-$\varepsilon$ turbulence closure scheme to quantify the effects of building height and street width on air quality within a street canyon oriented perpendicular to the wind. Because the $k$-$\varepsilon$ scheme is less computationally expensive than other schemes, they were able to simulate the canyon as two three-dimensional buildings in a larger computational domain. They defined a domain of interest, a volume in the center of the street canyon of a fixed length, spanning the entire width of the canyon (in the direction of the wind) and spanning from the ground to the height of the buildings. Notably, rather than simulating a point or line source in this street canyon, they applied a constant volume source to the domain of interest. Their concentration contour results for the study where they vary the building heights, $H$, for a fixed street canyon width, $D$, are shown in Figure 2-2. While someone with knowledge of the flow fields may be able to draw conclusions about why these contours vary so much for different building heights, or what the air quality implications may be, these conclusions may not be readily apparent to a less technical audience. To remedy this, Bady et al. [2008] used indoor ventilation efficiency parameters to quantify the air quality in the domain of interest rather than using only the mean or maximum concentration on a particular plane as their air quality metric, as shown in Figure 2-3. Figure 2-3 (a) shows how the average concentration in the domain of interest changes with increasing the height of the buildings, a standard metric. Figure 2-3 (b) quantifies the air exchange rate per hour for each case, defined as “the rate at which the total volume of air within the study domain is replaced with fresh air [Bady et al., 2008].” This metric is well understood by architects and urban designers with respect to indoor air quality, so it may be more useful than mean concentration data for conveying information about air quality in the street canyon. The visitation frequency, $VF$, shown in Figure 2-3 (c) shows the average number of times that a particle leaves the domain. A $VF$ of unity means that the particle never returns to the domain once it has left; a $VF$ of two means that the particle left the domain, returned to the domain and then left it again. The $VF$ is used in the calculation of the average residence time. The residence time of a particle is defined as “the time the particle takes from first entering (or
being generated in) the domain to its leaving [Bady et al., 2008].” $T_P$, shown in Figure 2-3 (d) is the average residence time for all particles in the domain.

The work of Bady et al. [2008] is an example of a quantitative parametric study, which almost meets the first goal of this thesis, however due to the simplicity geometry studied, the trends that they quantified are not applicable in a realistic urban setting. Their approach of studying how two independent geometric parameters independently affect the concentration (a dependent parameter) and the application of accepted indoor air quality metrics to the outdoors make this study exceptional. Their discussion of the flow fields provides the reader with only a limited physical understanding of the results because the discussion is restricted to two-dimensional phenomena. The results are summarized in such a way that an urban designer who is designing two 25 m-long buildings of the same height, oriented perpendicular to the wind could understand how changing the building height and the street canyon width would affect the air quality in the center volume of the street canyon, which meets the third goal of this thesis.

Graphics quantifying vertical mixing or air quality, generated based on rigorous parametric experimental investigations or parametric CFD simulations of urban-like geometry would be more useful to urban designers than any of techniques discussed in Sections 2.1 and 2.2 alone. In general, results should be presented in a format that is interesting to those in the urban design field, such as the output metric related to pedestrian comfort used by Reiter [2010] or the well understood indoor air quality metric used by Bady et al. [2008]. Parametric studies alone leave the user with a lack of physical understanding of the results however, which means that these studies cannot meet the second goal of this thesis: “to gain a physical understanding of the flow phenomena responsible for these quantitative results using fluid mechanics.” This lack of understanding also makes extrapolation of the results risky and makes them less compelling to a technical audience.
Figure 2-2: Concentration fields for different heights of street buildings, taken along the middle of the length of the street canyon: (a) $H/D = 0.4$; (b) $H/D = 0.6$; (c) $H/D = 0.8$; (d) $H/D = 1.0$. [Bady et al., 2008]

Figure 2-3: Effect of building height on the air quality parameters within the volume of interest (a) average concentration; (b) air exchange rate; (c) visitation frequency; (d) average residence time. [Bady et al., 2008]
2.4 Analytical approach

An analytical approach to studying the flow field in the UCL and the exchange between the UCL and the UBL would provide valuable physical insight and understanding of how urban geometries influence the transport and removal of scalars, such as heat and pollutants, from a neighborhood.

Hall et al. [2012] derived a simple analytical model for the mean horizontal velocity in an infinitely long street canyon aligned with the wind. They assumed the air in the street canyon was driven by a momentum exchange with the faster air above the street canyon. They used plume entrainment theory to express the exchange velocity as a function of the difference between the average wind velocity above the street canyon and the average velocity in the street canyon [Morton et al., 1956; Hall et al., 2012]. Using a control volume approach they solved for the bulk velocity in the street canyon as a function of the average velocity above the street canyon, the aspect ratio of the street canyon, the skin friction coefficient of the street canyon surfaces and some unknown exchange coefficient. They used CFD to find the exchange coefficient, thereby closing the model. This resulted in a simple, algebraic expression for the bulk velocity in the street canyon, which may be presented graphically, or evaluated quickly with a four-function calculator and would therefore be easily understandable to urban designers or policy makers.

Soulhac et al. [2008] developed an analytical model for the vertical and horizontal profiles of horizontal velocity in an infinitely long street canyon aligned with the wind. They first assumed that each point in the street canyon was only influenced by the nearest wall. Next they solved the Reynolds-averaged Navier-Stokes equations for the regions influenced by the side walls or building façades using separation of variables, Bessel functions and approximations of the turbulent diffusivity based on Prandtl’s mixing length theory, an example of an even simpler turbulence model than those discussed in Section 2.2.3 [Stull, 1988; Ferziger and Perić, 2002]. Finally, they used the similarity theory-based logarithmic law and profile matching to solve for the region influenced by the bottom wall or street. They evaluated these equations using
CFD. The resulting model is more complicated than Hall et al. [2012] and may not be understandable to the average urban designer. This model provides spatial information about the flow within the street canyon, however, which may be of interest when designing for natural ventilation, and it could be presented graphically for various cases rather than with the long equation, thereby making it more understandable to a non-technical audience.

These analytically-based models are derived from the conservation equations, thus the user may gain a physical understanding of the trends in the results, unlike the parametric studies in Section 2.3. It would be difficult to derive accurate analytical models for urban geometries more complex and realistic than an infinitely long street canyon, however, so this approach is not useful in the context of guidelines for urban designers. Even deriving analytical models for the bulk airflow in the UCL when the incident wind is at an angle to the infinite street canyon resulted in inaccuracies for both Hall et al. [2012] and Soulhac et al. [2008].

2.5 Physics-based approach

A physics-based approach to understanding the mixing between the UCL and the UBL involves using an understanding of the flow field around urban forms to explain the trends found in parametric studies, like those discussed in Section 2.3. The understanding of the physics should be robust enough that the results may be interpolated with confidence for parameter values within the range of a particular study.

Buccolieri et al. [2010] parametrically studied the effect of the packing density of cubic buildings in orthogonally gridded urban areas on city “breathability” using RANS simulations with a $k-\varepsilon$ turbulence closure scheme. The packing density is defined as the area of the buildings in plan view divided by the area of lot that they are located on. They simulated packing densities ranging from 0.0625 to 0.69 for 10 m cubic buildings spread over a square lot area of 136.5 x 136.5 m. This built up area was simulated within a larger domain. They discussed how the physics of the flow affected the concentrations in the UCL and presented the results using an indoor
ventilation metric, similar to those used by Bady et al. [2008] and shown in Figure 2-3. Their work provides a nice discussion of the flow phenomena responsible for the trends as the packing density parameter is varied. The indoor ventilation metric is never displayed as a function of building packing density in a summary graphic, however, an output that may have been of interest to urban designers. This could be due to the large spatial variability in the parameter around the gridded array largely caused by the consideration of this geometry on a flat plane, rather than in a more realistic setting (i.e. surrounded by other buildings of similar packing density). Many of the physical phenomena discussed in Buccolieri et al. [2010] are caused by the unrealistic situation of having no cubes upwind, downwind or adjacent to the array being simulated. This limits the applicability of their conclusions in realistic situations. The choice of packing density as the parameter of interest is also less than ideal. This is because the researchers have arbitrarily chosen to create cubic geometries and to vary packing density by varying the spacing of the cubes equally along the direction of the wind as well as perpendicular to the wind. Packing density may also be varied by changing the length and width of the buildings, however, or by changing the spacing of the cubes along only one axis of the grid. Therefore packing density is a combination of more than one independent geometric parameter defining a repetitive, orthogonally-gridded neighborhood. Each independent parameter may be responsible for influencing a given output metric, so it is impossible to isolate how each independent parameter is influencing their results. This is further evidenced in the work of Buccolieri et al. [2011], wherein they simulate the flow field around different geometries with the same packing densities as their previous work and find that the dimensionless concentration at pedestrian level is not equal for geometries of the same packing density.

Hang et al. [2010b] studied flow in long street canyons aligned with the wind using the RANS equations with a k-ε turbulence closure scheme. They provided thorough explanations of the flow mechanisms in these street canyons for various aspect ratios and canyon lengths in the direction of the wind. They calculated mean and turbulent momentum fluxes across the roofs of these street canyons and explained variations in
the fluxes due to changes in the canyon geometry using their understanding of the flow field. Hang et al. [2010b] noted that the mass flux in sufficiently long street canyons eventually becomes fully developed and that the ventilation in the fully developed region is due to turbulent fluxes in their geometry. They discussed how and why these fluxes vary when the street canyon has a sudden contraction or expansion halfway along its length. When the downstream part of the street canyon is wider they discovered a mass flux into the street canyon near the expansion due to the increased flow capacity inherent in the geometry of the wider street canyon, and they found that this effect was more pronounced due as the downstream section increased in width. When the downstream portion of the street canyon is narrower, they found a mass flux out of the street canyon near the contraction due to the decreased flow capacity of the narrower street canyon geometry. They also acknowledged the simplicity of their geometry relative to realistic urban forms. The parameters are not varied over a sufficiently wide range to consider this work a parametric study, and the graphics are not suitable for urban designers, however their physical understanding of the flow phenomena is impressive and meets the second goal of this thesis for their particular geometry.

A physics-based approach is taken in this thesis. Parametric studies similar to those discussed in Section 2.3 and this section, but with more complex and realistic urban forms, would meet the first goal of this research: “to quantitatively compare the vertical mixing potential of common urban forms as their geometries are parametrically varied.” The most simple geometric parameters in an orthogonally gridded city will be isolated in Chapter 4. These parameters will be used in the parametric work in this thesis so that each resultant trend may be attributed to a particular simple independent parameter. The trends will be explained based on a physical understanding of how the flow field changes as each simple independent parameter is varied. Variations due to changing multiple parameters at once will also be discussed. Understanding the physics responsible for changes in a single parameter will allow predictions of the effects of varying multiple parameters. For example, building length is varied in Section 5.1, building width is varied in Section 5.2 and both parameters
are varied in Section 5.3. The results in Section 5.3 could have been predicted based on the physical understanding developed in Sections 5.1 and 5.2. This technique will avoid the lack of true physical understanding of trends attained when using more complicated parameters such as packing density in parametric studies. Additionally, the geometries will be considered in a more realistic urban context, unlike much of the previous work in this chapter which presents results that are influenced by the fact that the geometries considered are two-dimensional or in the middle of a flat plate with no surrounding buildings. The second goal, “to gain a physical understanding of the flow phenomena responsible for these quantitative results using fluid mechanics,” cannot be met by parametric studies alone. Parametric studies could be enhanced by deriving a simple analytical model based on the conservation equations and a set of assumptions that explains the parametric results, which may be possible for some simply geometries as shown in Section 2.4. Another supplement to parametric studies is a careful inspection of the experimental or CFD flow fields to determine if there are some predictable (and possibly explainable with fluid mechanics) flow phenomena that are responsible for the trends in the results. Hang et al. [2010b] and Buccolieri et al. [2010] each do this to some extent. In the work of Reiter [2010], discussed in Section 2.3, the flow phenomena found when considering wind impinging on a single building was explained fluid mechanically by Gandemer [1975]. Reading the work of Gandemer [1975] and similar work by Hunt [1971] and Penwarden and Wise [1975] makes the results of Reiter [2010] far more compelling. Together, these works meet the second goal of this thesis for the single and two-building cases that they studied. A graphic visualizing the results of a parametric study using an output metric of interest to urban designers begins to meet the third goal of this thesis. This could be made more compelling with an explanation based on simple, perhaps schematic visualizations of the flow phenomena responsible for the trends in the results. These graphics meet the third goal of this thesis, “to summarize these results so they may be used by urban designers and policy maker to inform early phase urban designs and zoning policy.” Inspired by the work discussed in this chapter, and with the goals of
this research in mind, an approach for the work in this thesis is developed in Chapter 3.
Chapter 3

Approach

Repetitive, gridded neighborhoods are ubiquitous in urban areas as evidenced by Figure 3-1. Chapters 4-8 of this thesis focus neighborhoods of this typology.

Neighborhood geometries can be quantitatively compared by assessing their ability to vertically remove scalars, such as heat or pollutants, from the UCL to the UBL. These layers are shown schematically in Figure 1-2. To that end, Chapters 5-8 consider gridded neighborhoods that are surrounded by neighborhoods of the same geometry, both laterally and in the upwind and downwind directions, as shown in Figure 3-2. These idealized cases, which are simulated with periodic boundary conditions for the upwind and downwind boundaries and symmetry boundary conditions for the lateral boundaries, represent sections far enough into a repetitive urban area that the vertical growth of the momentum and turbulence boundary layers is small in comparison to the length of the city section considered along the free stream wind direction. In these scenarios the velocity and turbulence fields in the UCL are approximately fully developed. A constant and uniform, near-ground release of a passive scalar is used to assess the ability of each neighborhood geometry to remove scalars from the UCL to the UBL. After a sufficiently long time, the scalar-fields become fully developed in space among the fully developed velocity and turbulence fields, and the concentrations reach steady state. Any scalars that are advected downwind from the UCL of the considered neighborhood to the UCL of the downwind neigh-
Figure 3-1: Repetitive gridded neighborhoods within cities, from left to right: Savannah, Madrid, Los Angeles, Bari, Portland, Santa Monica, Philadelphia, San Francisco, Oakland, Barcelona, San Francisco, New York (Adapted from: Jacobs [1993])

neighborhood are simply replaced by the same amount of scalars advected into the UCL of the considered neighborhood by the UCL of the upwind neighborhood. Removing a scalar from the UCL in these cases is therefore only possible by vertical mixing. This is shown schematically in Figure 3-3, where $f_{in}$ is the flux of scalars into the considered neighborhood from the upwind neighborhood, $f_{out}$ is the flux of scalars out of the considered neighborhood and into the downwind neighborhood, $f_{vert}$ is the vertical flux of scalars from the UCL to the UBL and $S$ is a constant source. When the scalar field is fully developed, $f_{in} = f_{out}$.

The setup of the CFD simulations discussed in this thesis is explained in Section 3.1. The post-processing approach used to quantify the ability of a particular neighborhood geometry to vertically remove scalars is presented in Section 3.2. Section 3.3 describes the various scales at which the results in this thesis may be displayed,
Figure 3-2: Plan view schematic of a repetitive urban area

Figure 3-3: Section view schematic of a repetitive urban area with a near-ground species release

and assesses which is most appropriate for use by urban designers and policy makers. Finally, Section 3.4 restates the goals of this research in the context of how they can addressed by the outputs generated by the specific approach of this thesis.

3.1 CFD Setup

Unless otherwise specified, all CFD in this thesis was set up as described in Sections 3.1.1 - 3.1.3. The simulations were computed using ANSYS Fluent 14.5. The meshing approach used for computation domains is described in Section 3.1.1. Each domain was simulated in two stages. First the momentum and turbulence equations were
computed, discussed in Section 3.1.2, followed by the computation of a near-ground species release, discussed in Section 3.1.3.

3.1.1 Mesh

Each simulation domain is made up of an array of cuboids, which represent city blocks or buildings, separated by streets. A large volume, five times taller than the average building height in the domain, is placed above these blocks as specified as best practice for CFD around buildings [Franke et al., 2007]. The height of the large volume was increased in this work in cases with variations in building height to ensure that the upper part of the large volume had a flow field that was not greatly influenced by the large scale roughness due to the building volumes.

Unless otherwise specified, each domain was meshed with structured, hexahedral elements. The lower zone of each domain, depicted in Figure 3-4, defined as the space between the ground and the x,y-plane aligned with the roof of the tallest building, was meshed uniformly with 0.5 x 0.5 x 0.5 m elements. The layer of mesh elements that abut the z=0 m x,y-plane were set to a separate zone, known as the source zone, as shown in Figure 3-4. This zone will be discussed in detail in Section 3.1.3. The upper zone of each domain, defined as the space between the the x,y-plane aligned with the roof of the tallest building and the top of the domain, was meshed with elements of x,y dimensions of 0.5 x 0.5 m. The vertical dimension of the lowest layer of mesh elements in the upper section was set to 0.5 m. The vertical dimension grew at a rate of 15 percent or less with increasing z-position. This is within the best practice guideline in Franke et al. [2007], which specifies a maximum cell growth rate of 30 percent between consecutive mesh elements.

3.1.2 Momentum and turbulence calculations

The steady formulation of the momentum and turbulence equations was solved with the pressure-based solver for each domain using a RANS turbulence model, specifically the standard $k - \epsilon$ turbulence model. This decision is discussed and evaluated in
Appendix A. The street, building façade and roof surfaces were specified as wall boundary conditions. The roughness of each of these surfaces was set to a Nikuradse sand grain roughness of $k_s = 0.25$ m. The fully rough regime version of the ANSYS Fluent 13.0 rough wall function was used in all simulations, thus $0.25$ m is the largest possible roughness for the near-ground $0.5$ m cubic mesh elements as stated in ANSYS [2010] (discussed at length in Hall [2010] and Hall et al. [2012]). This is equivalent to a skin friction coefficient of approximately $1 \cdot 10^{-2}$ Hall [2010]. The ANSYS Fluent 13.0 rough wall function allows for a much coarser mesh near the wall than if using standard wall functions with a smooth wall. Therefore, simulating walls with a Nikuradse sand grain roughness of $0.25$ m allows use of a coarser overall mesh and thus a reduced computation time. Using rough wall functions are acceptable when the non-dimensional roughness height, $k_s^+$, defined as:

$$k_s^+ = \frac{k_s u_*}{\nu} \tag{3.1}$$

is greater than 90, meaning the flow is in the fully rough regime [ANSYS, 2012]. In Equation 3.1, $u_*$ is the friction velocity which is approximately one order of magnitude smaller than the incident wind speed. The kinematic viscosity used for air in ANSYS Fluent is $\nu = 1.46 \cdot 10^{-5}$ m$^2$/s. Using a wind speed of 1 m/s, the rough wall functions are accurate for $k_s > 1.3 \cdot 10^{-2}$ m. For a wind speed of 10 m/s, the rough wall
functions are accurate for $k_s > 1.3 \cdot 10^{-3}$ m. Realistic building façades are not smooth walls, but are often made of brick or other irregular materials with some roughness and have medium obstacles such as open windows and architectural details. They may also have larger obstacles such as balconies. This will lead to some non-negligible average roughness, as discussed in Hall [2010]. $k_s = 0.25$ m is used throughout this thesis as an upper bound for façades with small to medium obstructions such as open windows, architectural details and material roughness. Reducing this value will lead to reduced roughness and increased wind speeds at a neighborhood scale, however the observed flow phenomena will be similar as the other geometric parameters are varied parametrically, thus $k_s = 0.25$ m is used as a sort of worst case scenario throughout this work.

As discussed in Section 3.1, large-scale simulations can be accomplished through the use of periodic boundary conditions at the inlet and outlet surfaces, shown for a general case in Figure 3-4. This setup removes the sensitivity of the results to the initial velocity and turbulence profiles at the inlet boundaries because the momentum and turbulence fields are fully developed. This is meant to approximate the selected neighborhood in a situation where it is surrounded by similar neighborhoods in the upwind and downwind directions as shown in Figure 3-2. This is a more realistic scenario than impinging flow on a neighborhood of bluff bodies for dense, land-locked cities. A set mass flow rate was specified normal to the periodic boundary conditions. All other boundaries in the domain were set to symmetry boundary conditions to approximate a similar neighborhood bordering the domain in the lateral direction as shown schematically in Figure 3-2.

The pressure-velocity coupling method was set to “coupled” because it is more efficient and robust than the segregated algorithms for steady-state flows [ANSYS, 2012]. The pressure spatial discretization scheme was set to “PRESTO!” because it works well for flow fields with some rotation or swirl, which is a characteristic of the flow in street canyons perpendicular to the wind in the skimming flow regime [Oke, 1987; Baik et al., 2000; ANSYS, 2012]. The momentum, turbulent kinetic energy and turbulent dissipation rate discretizations were set to “second order upwind” to
reduce numerical diffusion inherent in first order upwind discretizations [Wendt, 2009; ANSYS, 2012].

The turbulent viscosity ratio limit was increased to $5 \cdot 10^{14}$ to ensure that the large-scale mixing was not inhibited in the neighborhood scale domains, discussed in detail in Hall [2010]. The solution was initialized using standard initialization. The initial value of the velocity normal to the inlet was set to 10% of the average velocity through the periodic inlet, while the other two velocity components were initialized with 0 m/s. The turbulent kinetic energy was initialized with a value $10^3$ times smaller than the square of the average velocity through the periodic inlet, and the turbulent dissipation rate was initialized with the default value of $1.0 \, \text{m}^2/\text{s}^3$.

These simulations were calculated using the pseudo transient under-relaxation method to improve stability and to reduce the number of iterations necessary to reach the steady state solution [Wendt, 2009; ANSYS, 2012]. For the first 1000 iterations a timescale factor of 0.1 was used with an aggressive length scale method. If this timescale factor led to divergence or oscillations in the solution, the simulation was rerun using the conservative length scale method. If this led to divergence or oscillations, the simulation was rerun with a timescale factor that was reduced by a factor of two. In rare cases (fewer than 10 in this entire thesis) this still led to divergence or oscillations, and in these cases the simulation was rerun after reducing the magnitude of each under-relaxation factor by 0.25. The remaining iterations were run with a time scale factor that was ten times larger than the previous value and with all other settings held constant. If this led to divergence or oscillations, the same steps were taken as with the first 1000 iterations.

The absolute convergence criterion for continuity, $x$, $y$ and $z$-velocity, turbulent kinetic energy and turbulent dissipation rate was set to $1 \cdot 10^{-10}$. Convergence was further ensured by monitoring $x$-velocity averaged over a $y,z$-plane bisecting a street canyon aligned with the wind as well as $z$-velocity averaged over an $x,y$-plane spanning between two roofs of neighboring buildings.
3.1.3 Species calculations

After the momentum and turbulence equations were fully converged, the species equation was simulated over each domain. The mesh elements closest to the ground were specified as a separate zone as shown in Figure 3-4. The carbon-monoxide-air mixture model was added to the simulation from the Fluent Database, and all materials were removed from the mixture besides air and carbon monoxide (CO). Next, a mass source and a CO source were added to the source zone near the ground. The sources were each set to $5 \cdot 10^{-4} \text{kg/(m}^3\text{-s)}$. Gravity was left at the default setting of “off,” so that the CO would act as a passive scalar released into the air.

The solver time was set to “transient,” and the transient formulation of the discretized equations was set to “second order implicit.” The species equation was then solved separately to simulate the source release into the steady, unchanging momentum and turbulence field. A transient simulation was used because the periodic boundary condition and finite height of the computational domain causes species in the volume to increase linearly for all time, as explained in Section 3.2, causing the steady species equation to never converge. This problem is addressed by simulating the species at particular time steps and then subtracting the linearly increasing portion of the data to find the steady solution as shown in Section 3.2. A relative convergence criterion of $5 \cdot 10^{-3}$ was set for CO. Finally, the time step size was set to satisfy the Courant-Friedrichs-Lewy (CFL) condition for the Courant number, $C$, as

$$\frac{u \Delta t}{\Delta x} \leq C_{\text{max}}, \quad (3.2)$$

where $u$ is the velocity, $\Delta t$ is the time step size, $\Delta x$ is the grid-cell size and $C_{\text{max}}$ is the maximum allowable value of the Courant number [Wendt, 2009]. This condition is meant to ensure that a parcel of fluid does not travel more than one grid-cell in any given time step. In the case of a three-dimensional CFD simulation meshed with hexahedral elements with edges that align with a Cartesian coordinate system, the
formulation for the time step size condition becomes:

$$\Delta t \leq \min \left( \frac{\Delta x C_{\text{max}}}{u_x}, \frac{\Delta y C_{\text{max}}}{u_y}, \frac{\Delta z C_{\text{max}}}{u_z} \right). \quad (3.3)$$

$C_{\text{max}}$ is unity for an explicit solver, however it can be higher for the more stable implicit solver used in these simulations [Wendt, 2009]. To ensure a conservative estimate for $\Delta t$, $C_{\text{max}}$ was considered unity. Using the greatest wind speed and the smallest grid-cell size for the CFL condition further ensures a stable transient solution. The smallest grid-cell size in any of the simulations was $0.5 \times 0.5 \times 0.5$ m, and the greatest average wind velocity through the periodic inlet was 10 m/s in many simulations, entirely in the x-direction. Using these values, $\Delta t$ was set to $5 \cdot 10^{-2}$ for all transient simulations with 10 m/s average velocity at the periodic inlet. The time step was modified using this approach for other values of average inlet velocities.

### 3.2 Post-processing and idealization

An unbiased comparison of how well two different neighborhood geometries are able to vertically mix out species, in this case passive scalars, from a near-ground source, can be made when the concentration field has reached steady state in the fully-developed momentum field. The ideal approach to assess vertical mixing would be to simulate a neighborhood using the domain shown in Figure 3-5(a). The shaded area near the ground represents the near-ground volume source of scalars, and the volume of interest is enclosed by the red, dashed line. In this case, the fluid above the control volume is assumed to be infinitely large such that it acts as a sink for the scalars while maintaining a concentration of zero.

A periodic boundary condition is used to calculate the fully-developed momentum field in the simulations in this thesis as discussed in Section 3.1.2. The inlet and outlet boundary conditions remain periodic as the species calculations are carried out as described in Section 3.1.3. This is meant to approximate the condition shown in Figure 3-5(a), however the actual behavior is shown in Figure 3-5(b). In Figure 3-5(b)
control surface 7 is set to a symmetry boundary condition, as discussed in Section 3.1.2. The height of the schematic drawing of control surface 6 is no longer infinite, but is set to at least five times the average building height in the domain as discussed in Section 3.1.1 after the guidelines described in [Franke et al., 2007]. This will result in a build up of species in the large volume above, which may bias the results when comparing two different neighborhood geometries with different heights for the large volumes above. The implications for finding the steady state concentration fields can be assessed by analytically solving the species equation for each of these cases.

\[
\frac{\partial \rho \phi}{\partial t} + \frac{\partial}{\partial x_i} \left( \rho u_i\phi \right) = \frac{\partial}{\partial x_i} \left( \rho D \frac{\partial \phi}{\partial x_i} \right) + S, \tag{3.4}
\]
where $\rho$ is the density of the fluid, a constant in the case of a passive scalar release into an incompressible fluid, $\phi$ is the mass fraction of the species, $u_i$ is the velocity, $D$ is the mass diffusivity coefficient for the scalar and air and $S$ is the volume source term of units $\text{kg/(m}^3\cdot\text{s})$. The instantaneous quantities in Equation 3.4 can be expanded using Reynolds decomposition to separate the time-averaged components from the fluctuation components as:

$$\frac{\partial \rho (\bar{\phi} + \phi')}{\partial t} + \frac{\partial}{\partial x_i} \left( \rho (\bar{u}_i + u_i') (\bar{\phi} + \phi') \right) = \frac{\partial}{\partial x_i} \left( \rho D \frac{\partial (\bar{\phi} + \phi')}{\partial x_i} \right) + S, \quad (3.5)$$

where $\bar{\phi}$ is the time-averaged component of the species mass fraction, $\phi'$ is the fluctuating component of the species mass fraction, and $\bar{u}_i$ and $u_i'$ are the time-averaged and fluctuating components of the velocity, respectively. Time-averaging Equation 3.5 yields the Reynolds-averaged species equation:

$$\frac{\partial \rho \bar{\phi}}{\partial t} + \frac{\partial}{\partial x_i} \left( \rho \bar{u} \bar{\phi} \right) + \frac{\partial}{\partial x_i} \left( \rho u_i' \bar{\phi} \right) = \frac{\partial}{\partial x_i} \left( \rho D \frac{\partial \bar{\phi}}{\partial x_i} \right) + S. \quad (3.6)$$

Some scalar transport terms in Equation 3.6 may be much smaller in magnitude than others for a particular problem, and these terms can be neglected to simplify analysis. The terms are compared for the domains in Figure 3-5 by estimating the time scales associated with the process that each term represents. The first term on the right hand side of Equation 3.6 represents mass diffusion, and the time scale associated with diffusing the scalar into air, $t_d$, is

$$t_d = \frac{H^2}{D}, \quad (3.7)$$

where $H$ is the length scale associated with vertical mixing, in this case the average building height in the neighborhood. The second term on the left hand side of Equation 3.6 represents the advection of the scalar by the mean flow field, and the time scale associated with advecting the scalar, $t_a$, is

$$t_a = \frac{H}{\bar{u}}, \quad (3.8)$$
where \( \bar{u} \) is a time-averaged, characteristic vertical velocity. The ratio of these times, \( t_d/t_a \), is known as the Peclet number:

\[
Pe = \frac{\bar{u}H}{D}.
\]  

(3.9)

This thesis is focused on cases where there is a non-negligible atmospheric wind speed driving air through the UCL. Conservative estimates of these variables are:

\( O(H) = 10 \) m, \( O(D) = 10^{-5} \) m²/s and \( O(u) = 0.1 \) m/s. Using these estimates, the Peclet number is three orders of magnitude larger than unity, and thus the mass diffusion term in Equation 3.6 may be ignored.

The third term on the left hand side of Equation 3.6 is the turbulent transport term, also known as the turbulent diffusion term. The time scale associated with turbulent diffusion of the scalar in the vertical direction, \( t_{dT} \), is

\[
t_{dT} = \frac{H}{u'},
\]

(3.10)

where \( u' \) is the characteristic fluctuating velocity in the vertical direction. The ratio of the turbulent diffusion time to the advection time, \( t_{dT}/t_a \), is known as the turbulent Peclet number, \( Pe_T \), which in this case reduces to:

\[
Pe_T = \frac{\bar{u}}{u'}.
\]

(3.11)

Though the exact ratio of the characteristic time-averaged vertical velocity to the characteristic fluctuating vertical velocity will be a function of neighborhood geometry, it is clear that a vertical velocity associated with turbulent diffusion or mean advection will dominate vertical mixing in the domains shown in Figure 3-5. Therefore, a general characteristic velocity, \( u \), can be considered to encompass both advection and turbulent diffusion in the following control volume arguments.

Assuming the species in the control volume in Figure 3-5(a) is well mixed and of concentration \( c_{B1} \), and the volume above is an infinite species sink of concentration \( c_{A1} = 0, c_{B1} (t) \) can be solved analytically using the unsteady control volume equation
with a source:

$$\frac{d}{dt} \int_{V_{B_1}} c_{B_1} (t) \, dV_{B_1} = \int_{A_i} u_i \left( c_i (t) - c_{B_1} (t) \right) \, dA_i + \int_{V_s} S \, dV_s, \quad (3.12)$$

where $V_{B_1}$ is the volume of the control volume, $u_i$ is a characteristic velocity associated with and normal to control surface $i$, $A_i$ is the area of control surface $i$, $c_i$ is the average concentration in the volume adjacent to the control volume and control surface $i$, $S$ is the volume source term, and $V_s$ is the volume of the source.

In Figure 3-5(a), control surface 1 encompasses all of the solid ground and building surfaces within the control volume, and has a zero flux of species across its surface. By definition of the periodic boundary condition, the flux of species into the control volume across control surface 2 is equal to the flux of species out of the control volume across surface 3. The generation term is equal the volume release rate of CO into the lowest cell zone, and is measured in $[\text{kg}/(\text{m}^3 \cdot \text{s})]$. There is a net flux of species across control surface 4 due to a characteristic vertical velocity, $u_4$. Therefore, Equation 3.12 simplifies to:

$$\frac{d}{dt} \int_{V_{B_1}} c_{B_1} (t) \, dV_{B_1} = \int_{A_4} u_4 \left( c_{A_1} (t) - c_{B_1} (t) \right) \, dA_4 + \int_{V_s} S \, dV_s. \quad (3.13)$$

After integrating over known volumes and areas, Equation 3.13 may be rewritten as:

$$\frac{d}{dt} c_{B_1} (t) = -\frac{A_4}{V_{B_1}} u_4 c_{B_1} (t) + \frac{V_s}{V_{B_1}} S. \quad (3.14)$$

This is a forced, first-order, ordinary differential equation, thus the complimentary solution is:

$$c_{B_1C} (t) = M_1 e^{-M_2 t}, \quad (3.15)$$

where $M_1$ and $M_2$ are constants. The particular solution is

$$c_{B_1P} (t) = M_3, \quad (3.16)$$
where \( M_3 \) is a constant, and the total solution is

\[
c_{B1}(t) = M_3 + M_1 e^{-M_2 t}.
\] (3.17)

With zero as an initial condition for \( c_{B1} \),

\[
c_{B1}(t = 0) = 0,
\] (3.18)

the constants equal:

\[
M_1 = -\frac{V_s S}{A_4 u_4},
\] (3.19)

\[
M_2 = \frac{A_4 u_4}{V_{B1}}
\] (3.20)

and

\[
M_3 = \frac{V_s S}{A_4 u_4}.
\] (3.21)

In the idealized case, the steady-state concentration is equal to \( M_3 \) and the time constant of the process is equal to the inverse of \( M_2 \).

Consider the control volumes shown in Figure 3-5(b). Assuming the concentrations \( c_{B2} \) and \( c_{A2} \) are well mixed, the equation for the concentration in the lower control volume is similar to Equation 3.14, except it is coupled to the concentration in the upper control volume as:

\[
\frac{d}{dt} \int_{V_{B2}} c_{B2}(t) \, dV_{B2} = \int_{A_4} u_4 (c_{A2}(t) - c_{B2}(t)) \, dA_4 + \int_{V_s} S dV_s,
\] (3.22)

where \( V_{B2} \) is the volume of the lower control volume. The control volume equation for the upper control volume is:

\[
\frac{d}{dt} \int_{V_{A2}} c_{A2}(t) \, dV_{A2} = \int_{A_4} u_4 (c_{B2}(t) - c_{A2}(t)) \, dA_4.
\] (3.23)

Equations 3.22 and 3.23 reduce to

\[
\frac{d}{dt} c_{B2}(t) = \frac{A_4}{V_{B2}} u_4 (c_{A2}(t) - c_{B2}(t)) + \frac{V_s}{V_{B2}} S
\] (3.24)
and
\[ \frac{d}{dt}c_{A2}(t) = \frac{A_1}{V_{A2}}u_4(c_{B2}(t) - c_{A2}(t)), \quad (3.25) \]
respectively.

Equations 3.24 and 3.25 are a pair of coupled, first-order, ordinary differential equations with a zero eigenvalue. The solutions to these equations are of the form:

\[ c_{B2}(t) = K_9t + K_1 + K_3e^{-K_4t}, \quad (3.26) \]

and

\[ c_{A2}(t) = K_{10}t + K_5 + K_7e^{-K_{10}t}, \quad (3.27) \]
respectively.

The constants are analytically solved using MATLAB’s ordinary differential equation and system solver, `dsolve`, as:

\[ K_1 = \frac{V_sS}{A_4u_4} \left( \frac{V_{A2}^2}{(V_{A2} + V_{B2})^2} \right), \quad (3.28) \]

\[ K_3 = -\frac{V_sS}{A_4u_4} \left( \frac{V_{A2}^2}{(V_{A2} + V_{B2})^2} \right), \quad (3.29) \]

\[ K_4 = \frac{A_4u_4}{V_{B2}} \left( \frac{V_{A2} + V_{B2}}{V_{A2}} \right), \quad (3.30) \]

\[ K_9 = \frac{V_s}{V_{A2} + V_{B2}}, \quad (3.31) \]

\[ K_5 = -\frac{V_sS}{A_4u_4} \left( \frac{V_{A2}V_{B2}}{(V_{A2} + V_{B2})^2} \right), \quad (3.32) \]

\[ K_7 = \frac{V_sS}{A_4u_4} \left( \frac{V_{A2}V_{B2}}{(V_{A2} + V_{B2})^2} \right), \quad (3.33) \]

\[ K_8 = \frac{A_4u_4}{V_{B2}} \left( \frac{V_{A2} + V_{B2}}{V_{A2}} \right), \quad (3.34) \]

and

\[ K_{10} = \frac{V_s}{V_{A2} + V_{B2}}. \quad (3.35) \]
The constants $K_9$ and $K_{10}$ are not a function of the flow field and are easily calculable based on the geometry of the domain. This means that the first term of Equations 3.26 and 3.27 can be subtracted from the CFD results at any given time step to get one step closer to converting the simulated result for the steady state concentration in the lower control volume, displayed computed in Equation 3.26 to the idealized result as in Equation 3.17. Consider a case where the source is taken to be in the lowest 0.5 m of the domain and with a magnitude of $5 \cdot 10^{-4}$ kg/(m$^3$-s) and the characteristic velocity is assumed to be 0.1 m/s for a domain with orthogonally gridded buildings with lengths of 80 m, widths of 80 m, heights of 20 m and street canyon aspect ratios of 2 (i.e. 10 m wide streets). In this case the vertical dimension of the large upper volume, shown schematically in Figure 3-5(b) was set to 100 m. The solid blue line in Figure 3-6 shows the concentration in the control volume in Figure 3-5(a) (Equation 3.17), the dashed green line shows the concentration in the lower control volume in Figure 3-5(b) (Equation 3.26) and the red squares a more idealized version of the green dashed line case, generated by subtracting the linear term, $K_9 t$, from Equation 3.26 as

$$c_{Bred} (t) = K_1 + K_3 e^{-K_4 t}. \quad (3.36)$$

If $V_{A2} \gg V_{B2}$, then $K_1 \to M_3$, $K_3 \to M_1$ and $K_4 \to M_2$. This makes sense because the upper control volume in Figure 3-5(b) approaches a species sink as in Figure 3-5(a) when it is much larger than the lower control volume. This means that the ideal solution shown in Figure 3-5 can be further approximated from data taken from a CFD simulation in a domain similar to Figure 3-5(b) by multiplying the data less the ramp term by a geometric constant,

$$N = \frac{(V_{A2} + V_{B2})^2}{V_{A2}^2}. \quad (3.37)$$

This constant is based on the ratio of steady state concentration analytically computed for the idealized lower volume to the steady state concentration found in the more realistic lower volume. This is based on setting $t \to \infty$ in the ratio of Equation
3.17 to Equation 3.36. Multiplying the steady state concentration in the simulated case by the ratio of the concentration in the ideal case to the simulated case (Equation 3.37), converts the simulated case to the ideal case. This conversion results in the black circles shown in Figure 3-6 and presented analytically as:

\[ c_{Bideal}(t) = M_3 + M_1 e^{-K_b t}. \]  

(3.38)

This result is different from Equation 3.17 only by the value of its time constant, which is slightly smaller than the one in Equation 3.17. Because the primary interest of this work is in computing the steady-state concentrations, this small deviation in time constant is acceptable. The time constant can be corrected by multiplying the simulated time constant by

\[ P = \frac{V_{A2}}{V_{A2} + V_{B2}}. \]  

(3.39)

Unless otherwise specified, species concentration was simulated in domains like Figure 3-5(b) and then was post-processed in the following steps:

1. Simulate each domain for various time steps (choice of time steps discussed in Chapter 6).
2. Subtract the ramp term, \( K_9 t \) (from Equation 3.31), from \( c_{B2}(t) \), the simulated neighborhood-averaged concentration data.
3. Fit the \( c_{B2}(t) \) data to Equation 3.36, solving for the steady state concentration and the time constant.
4. Idealize the steady state concentration found through simulation and fitting by multiplying it by \( N \) from Equation 3.37.
5. Idealize the time constant found through simulation and fitting by multiplying it by \( P \) from Equation 3.39.
Figure 3-6: Graphical explanation of post-processing approach, shown using analytical equations

3.3 Scale of interest

It is important to present the results in a way that is useful to the intended audience. Part of this presentation includes choosing the correct scale to display the results.

3.3.1 Sub-grid scale and grid scale

Sub-grid scale results refer to any data that is at a finer resolution than the CFD mesh discussed in Section 3.1.1. According to Ferziger and Perić [2002], one common application of this type of data is as a research tool for "understanding the mechanisms of turbulence production, energy transfer and dissipation in turbulent flows."

Grid-scale results would be useful to researchers interested in evaluating their simulation data. The velocity and turbulence data at each mesh node may be compared
to available analytical solutions, experimental data or simulations with more exact, but more computationally intensive, turbulence models.

In this thesis, grid-scale simulation data will be used to understand the flow phenomena responsible for trends in steady state concentrations in the considered neighborhoods. These two scales are too fine to be useful to urban designers or policy makers.

### 3.3.2 Street canyon scale

Street canyon scale data refers to measurements of properties bulk-averaged over volumes in the UCL. For the purposes of the orthogonally-gridded neighborhood work in Chapters 4–8, where one axis of the grid is aligned with the wind, UCL volumes are defined in plan as in Figure 3-7. These volumes span from street level to either pedestrian height, minimum building height in the neighborhood or average building height in the neighborhood depending on the application of the results.

Results at this scale may be interesting to urban designers. If tasked with placing an outdoor seating area for a corner café, for example, a designer may consider which of the three volume types in Figure 3-7 is likely to have the lowest pollutant concentrations and the most desirable wind speeds at pedestrian height during the months when outdoor seating is possible.

### 3.3.3 Neighborhood scale in the UCL

Neighborhood scale data refers to measurements of properties bulk-averaged over the UCL of the repeated, periodic units of the domains in Chapters 4–8. In Figure 3-7 this would encompass all of the long canyons, cross canyons and intersections in a particular neighborhood.

Results at this scale may be interesting to policy makers. If tasked with considering future air quality of a gridded neighborhood in the early design phase, policy makers could set upper and lower bounds on parameters such as intersection frequency, street canyon aspect ratio, building height variation and percent of land area
3.3.4 City scale and UBL data

City scale and UBL data refers to velocity, turbulence or other profiles simulated or measured in and above urban areas. This data is often displayed as a function of the vertical dimension, $z$, and may be averaged laterally over the city or measured at one point in the $x, y$-plane. This scale of data is useful for understanding the large-scale effects of the city on the velocity and turbulence fields. In these situations, the city is considered a rough surface that modifies the flow fields at a large enough scale as to have an impact on neighboring suburban and rural areas. This type of data is interesting to meteorologists interested in accurately predicting atmospheric conditions above and downwind of an urban area [Oke, 1987; Stull, 1988]. This data would be too coarse to inform the work of urban designers or policy makers, however it could be used to influence environmental policy in the future.
3.4 Goals, achieved using a physics-based approach informed by simulation

The main goals of this research are restated in the context of the approach outlined in Sections 3.1 - 3.3 as:

- To quantitatively compare the vertical mixing potential of common urban forms as their geometries are parametrically varied by assessing their steady state concentrations at both street canyon and neighborhood scales
- To gain insight into the flow phenomena responsible for these quantitative results using fluid mechanics and grid-scale simulation data
- To summarize these results at both street canyon and neighborhood scales so they may be used by urban designers and policy makers to inform early phase planning and zoning policy
Chapter 4

Dimensional arguments

Dimensional arguments will be used in this thesis to increase the utility of a single CFD simulation, meaning that a single simulation may represent more than a single point in the design space; it may be extended to cover variations in one or two relevant independent parameters. Section 4.1 considers how the velocity in the street canyons aligned with the wind will vary with Reynolds number for repetitive, gridded neighborhoods aligned with the wind. In Section 4.2, the relationship between volume source release rate and the steady-state concentration in the UCL is derived. Section 4.3 discovers how the steady-state concentration varies when changing average velocity through the inlet of a given domain and defines the non-dimensional concentration used throughout this thesis.

4.1 Reynolds number

Consider a domain representing an idealized gridded neighborhood with buildings of constant height, shown schematically in Figure 4-1. The dashed lines represent the periodic and symmetry boundary conditions used to approximate an infinitely long, repeating neighborhood as discussed in Section 3.1.

The velocity of the wind in the x-direction, averaged over the volume of the long canyons aligned with the wind (defined in Figure 3-7) is known as $u_c \, [\text{m/s}]$. Because
the flow is steady and fully developed, \( u_c \) will not be a function of time. \( u_c \) is a function of the density of the fluid, \( \rho \) [kg/m\(^3\)], the dynamic viscosity of the fluid, \( \mu \) [kg/(m-s)], the average wind speed flowing through inlet of the domain (volumetric flux through the inlet boundary condition divided by the area of the inlet boundary), \( u_a \) [m/s], the skin friction coefficient of the wall boundary conditions, \( C_f \), and the five simplest length scales that completely describe the geometry of the domain, defined in Figure 4-1 as \( L \) [m], \( W \) [m], \( H \) [m], \( L_{int} \) [m] and \( W_{int} \) [m]. This is shown in equation form as:

\[
  u_c = f_1(\rho, \mu, u_a, C_f, L, W, H, L_{int}, W_{int}). 
\]  

Equation 4.1 has three fundamental physical dimensions: mass, length and time, expressed in SI units as [kg], [m] and [s], respectively. With nine independent variables on the right hand side of the equation and three fundamental dimensions, Equation 4.1 will reduce to having six independent variables after being simplified through dimensional arguments.

The first term on the left hand of Equation 4.1, \( \rho \), will be non-dimensionalized first. The mass units may be removed from this term by dividing it by another term that has the physical dimension of mass from the right hand side of the equation,
which in this case must be $\mu$ [kg/(m-s)], resulting in:

$$u_c = f_2 \left( \frac{\rho}{\mu}, \mu, u_a, C_f, L, W, H, L_{int}, W_{int} \right). \quad (4.2)$$

Because $\mu$ is the only term on the right hand side of Equation 4.2 with units of mass and because $u_c$ does not have units of mass, $u_c$ cannot be a function of $\mu$ so Equation 4.2 reduces to

$$u_c = f_3 \left( \frac{\rho}{\mu}, u_a, C_f, L, W, H, L_{int}, W_{int} \right). \quad (4.3)$$

The first term on the right hand side of Equation 4.3, $\rho/\mu$ [s/m$^2$], may be further non-dimensionalized by eliminating the time dimension by multiplying the term by $u_a$. This results in:

$$u_c = f_4 \left( \frac{\rho u_a}{\mu}, u_a, C_f, L, W, H, L_{int}, W_{int} \right). \quad (4.4)$$

The first term on the right hand side of Equation 4.4, $\rho u_a/\mu$ [1/m], may be non-dimensionalized by multiplying it by one of the geometric parameters from the right hand side of the equation as

$$u_c = f_5 \left( \frac{\rho u_a W_{int}}{\mu}, u_a, C_f, L, W, H, L_{int}, W_{int} \right). \quad (4.5)$$

The first term on the right hand side of Equation 4.5 is now dimensionless, and is known as the Reynolds number, a measure of the ratio of the inertial forces to the viscous forces for a given flow field.

The second term on the right hand side of Equation 4.5 is now the only term on the right hand side with the fundamental physical dimension of time. This term must then be used to remove the dimension of time from the left hand side:

$$\frac{u_c}{u_a} = f_6 \left( \frac{\rho u_a W_{int}}{\mu}, C_f, L, W, H, L_{int}, W_{int} \right). \quad (4.6)$$

The left hand side of Equation 4.6 is now dimensionless.
The five length scales that define the geometry in Figure 4-1 on the right hand side of Equation 4.6 have units of length. All but one of these variables may be non-dimensionalized with the remaining length scale as:

\[
\frac{u_c}{u_a} = f_7 \left( \frac{\rho u_a W_{int}}{\mu}, C_f, \frac{L}{W_{int}}, \frac{W}{W_{int}}, \frac{H}{L_{int}}, \frac{L_{int}}{W_{int}} \right) .
\]  

(4.7)

Equation 4.7 essentially states that the flow field in the UCL will be a function of the geometry of the domain, the roughness of the walls of the domain and the Reynolds number of the flow. The value of this roughness can be expressed for the cases studied in this thesis (which are in the fully rough regime) in terms of the dimensionless skin friction coefficient, \(C_f\), as:

\[
C_f = \frac{1}{4} \left( 1.74 + 2 \log_{10} \left( \frac{D_h}{2 k_s} \right) \right)^{-2} ,
\]  

(4.8)

where \(D_h\) the hydraulic diameter, taken to be approximately \(W_{int}\) [Nikuradse, 1950; Mills, 1998; Hall, 2010]. For a Nikuradse sand grain roughness of 0.25 m, chosen based on the discussion in Section 3.1.2, and \(W_{int} = 10\) m; Equation 4.8 results in \(C_f \approx 1.1 \cdot 10^{-2}\). Similar flow fields in Hall [2010] were found to be independent of Reynolds number at large enough values of Reynolds number. This independence is tested for the domain shown in Figure 4-1 where \(\rho = 1.225\) kg/m\(^3\), \(\mu = 1.7894 \cdot 10^{-5}\) kg/(m-s), \(u_a = 10\) m/s, \(C_f \approx 1.1 \cdot 10^{-2}\), \(L = 80\) m, \(W = 80\) m, \(H = 20\) m, \(L_{int} = 10\) m and \(W_{int} = 10\) m. This domain was meshed and simulated following the procedure in Sections 3.1.1-3.1.2 for five values of \(u_a\), varying from 2 m/s to 10 m/s in increments of 2 m/s. The results are shown in Figure 4-2, expressed in terms of \(u_a\) as well as the non-dimensional, independent parameter, Reynolds number.

Additionally, dependence on Reynolds number was tested by varying \(W_{int}\) from 10-50 m, while keeping all other non-dimensional parameters in Equation 4.7 constant. In these cases \(u_a = 10\) m/s, the meshes were directly scaled with \(W_{int}\) and the simulations were set up as described in Section 3.1.2. These results are presented in Figure 4-3 and are expressed in terms of the Reynolds number as well as \(W_{int}\). 
Figure 4-2: \( \frac{u_c}{u_a} \) vs. Reynolds number and \( u_a \) [m/s] for an idealized gridded neighborhood

\( \frac{u_c}{u_a} \) is not a function of \( u_a \) for the range of values tested. The root-mean-square deviation of the values in Figure 4-2 is \( 6.6 \cdot 10^{-4} \). Normalizing by the average value of \( \frac{u_c}{u_a} \), leads to a coefficient of variation of root-mean-square deviation of \( 3.3 \cdot 10^{-3} \), certainly small enough to consider \( \frac{u_c}{u_a} \) to be independent of \( u_a \) in this range. Additionally, \( \frac{u_c}{u_a} \) is not a function of \( W_{int} \), as shown in Figure 4-3. The root-mean-square deviation in this case is \( 2.5 \cdot 10^{-5} \) resulting in a coefficient of variation of root-mean-square deviation of \( 1.2 \cdot 10^{-4} \). These results prove that \( \frac{u_c}{u_a} \) is not a function of Reynolds number for the range of \( 1.4 \cdot 10^6 \) to \( 3.4 \cdot 10^7 \). This means that if the momentum equations are simulated around a particular building geometry for a particular magnitude and direction of wind velocity, the resulting velocity fields may simply be scaled to predict the velocity fields for other wind velocities with the same orientation.
4.2 Release rate

The steady-state concentration of a species at a particular point in space, \( c(x, y, z) \), is measured in kg/m³. The relevant concentration for urban planning applications will be averaged over some bulk volume of interest in the UCL. This is generally defined as

\[
C_{ss} = \frac{1}{V} \int_x \int_y \int_z c(x, y, z) \, dx \, dy \, dz \quad (4.9)
\]

where \( C_{ss} \) [kg/m³] is the steady-state concentration averaged over some volume, \( V \) [m³].

Consider the repetitive gridded-neighborhood shown in Figure 4-1 with a constant, uniform release of passive scalar near the ground, simulated as described in Section 3.1.3 for various time steps and shown schematically in Figure 3-4. \( H_s \) is the vertical
height of the near-ground volume source release, and \( H_s = 0.5 \) for all simulations in this thesis unless otherwise specified. \( C_{ss} \) is averaged over the UCL and is post-processed as described in Section 3.2, making it a steady-state value and not a function of time. \( C_{ss} \) is a function of the volumetric release rate, \( S \) \([\text{kg}/(\text{s-m}^3)]\), and the previously defined parameters: \( u_a, C_f, H_s, L, W, H, L_{int} \) and \( W_{int}, \rho \) and \( \mu \). For simplicity, the density and viscosity are presented in terms of the kinematic viscosity, \( \nu = \mu/\rho \), which has units of \( \text{m}^2/\text{s} \). This shown in equation form as:

\[
C_{ss} = g_1 (\nu, S, u_a, C_f, H_s, L, W, H, L_{int}, W_{int}).
\]  

(4.10)

The variables in Equation 4.10 contain three unique fundamental dimensions: mass, length and time. The kinematic viscosity may be non-dimensionalized following the reasoning developed in Equations 4.3-4.5. This results in

\[
C_{ss} = g_2 \left( \frac{\nu}{u_a W_{int}}, S, u_a, C_f, H_s, L, W, H, L_{int}, W_{int} \right),
\]  

(4.11)

where the first term on the right hand side may be inverted and presented as the Reynolds number:

\[
C_{ss} = g_3 (\text{Re}, S, u_a, C_f, H_s, L, W, H, L_{int}, W_{int}).
\]  

(4.12)

Next, consider \( S \), which is the only parameter on the right hand side of Equation 4.12 with units of mass, thus it cannot be non-dimensionalized with the other parameters from the right hand side of the equation and must be used to remove the units of mass from the left hand side of the equation. This results in:

\[
\frac{C_{ss}}{S} = g_4 (\text{Re}, u_a, C_f, H_s, L, W, H, L_{int}, W_{int})
\]  

(4.13)

Equation 4.13 states that for a repetitive gridded neighborhood aligned with the wind, shown in Figure 4-1, with constant Reynolds number, building geometry parameters \( (L, W, H, L_{int}, W_{int}) \), surface roughness \( (C_f) \), and average wind speed
flowing through the inlet of the domain \((u_a)\), the steady-state concentration averaged over a volume divided by the near-ground volumetric release rate, \(C_{ss}/S [s]\), will not be a function of \(S\). This means that \(C_{ss}/S\) will be constant as \(S\) is varied. This was evaluated with CFD using the techniques described in Sections 3.1-3.2. The geometric variables and surface roughness were the same as those used in Section 4.1, \(u_a = 10 \text{ m/s}\), the time step size was set to 0.05 s following Equation 3.3, the time steps used for post processing were 0, 60, 120, 240 and 960 s (discussed in Chapter 6) and \(S\) was varied from \(1 \cdot 10^{-4}\) to \(9 \cdot 10^{-4} \text{ kg/(s-m}^3)\) in increments of \(2 \cdot 10^{-4} \text{ kg/(s-m}^3)\). The steady-state results are shown in Figure 4-4.

As expected, \(C_{ss}/S\) appears to be constant in Figure 4-4. The root-mean-square deviation of the \(C_{ss}/S\) data is \(3.6 \cdot 10^{-2} \text{ s}\). Normalizing by the average value of \(C_{ss}/S\) produces a coefficient of variation of root-mean-square deviation of \(5.3 \cdot 10^{-3}\), which is small enough to consider \(C_{ss}/S\) a constant. This means that if the value of \(C_{ss}/S\) is known for a particular case, \(C_{ss}\) may simply be scaled with \(S\) to approximate real-
world changes in $S$ such as increases in the number of vehicles due to time of day or changes in population.

### 4.3 Atmospheric velocity and non-dimensional concentration

The only term with the dimension of time on the right hand side of Equation 4.13 is $u_a$, therefore it cannot be non-dimensionalized with parameters from the right hand side of the equation. It may however be used to remove the time dimension from the left hand side of the equation as,

$$\frac{C_{ss} u_a}{S} = g_5 (\text{Re}, C_f, H_s, L, W, H, L_{int}, W_{int}).$$  \hspace{1cm} (4.14)

Equation 4.14 states that for a given neighborhood like the one shown in Figure 4-1, with all parameters on the right hand side of the equation held constant, $C_{ss} u_a/S$ [m] will not be a function of $u_a$. This means $C_{ss} u_a/S$ will be constant, even as $u_a$ varies. This was evaluated using CFD, which was setup as described in Sections 2.2-3.2. The geometric variables and surface roughness were the same as those used in Section 4.1, $S = 5 \cdot 10^{-4}$ and $u_a$ was varied from 2 to 10 m/s in increments of 2 m/s. The time step sizes, $\Delta t$ used for post-processing were found using Equation 3.3, and are shown in Table 4.1. Knowing how the time constant varies with $u_a$ from Equation 3.30, and using methods to be discussed in Chapter 6 the time steps used for post-processing, $t_0, t_1, t_2, t_3$ and $t_4$, were scaled from those selected in Section 4.2 and are displayed in Table 4.1. The steady state results for $C_{ss} u_a/S$ are shown in Figure 4-5.

Figure 4-5 shows that $C_{ss} u_a/S$ is approximately a constant for variations in $u_a$. The root-mean-square deviation for the $C_{ss} u_a/S$ data is $2.8 \cdot 10^{-1}$ m, yielding a coefficient of variation of root-mean-square deviation of $4.1 \cdot 10^{-3}$ when normalized by the average value of $C_{ss} u_a/S$. This is a small enough coefficient of variation to assume that $C_{ss} u_a/S$ is not a function of $u_a$. This information allows a single simulation to predict the concentration for changing meteorological wind speeds.
In this thesis the height of the near-ground volume source release, $H_s$, is always the vertical height of the grid volume adjacent to the bottom of the domain. In most simulations this value was equal to 0.5 m as described in Section 3.1.1. In larger domains, however, it was necessary to increase the grid size near the ground to 1.0 m, and thus $H_s$ must be increased to 1.0 m as well. For small values of $H_s/H$, (based on flow field observations in this thesis: $H_s/H < 0.05$) the volume source approximates
a ground area source. Therefore, decreasing $H_s$ by some factor simply decreases the species in the domain by that factor. This is the same as decreasing $S$ by the same factor. Following these arguments and the results of Section 4.2 it makes sense to use $H_s$ to non-dimensionalize $C_{ss \, u_a}/S$ as

$$\frac{C_{ss \, u_a}}{S \, H_s} = g_6 \left( \text{Re}, C_f, H_s, L, W, H, L_{int}, W_{int} \right),$$  \hspace{1cm} (4.15)

where the term on the left hand side of this equation is a non-dimensional concentration. Based on the previous arguments and the results in Section 4.2, $(C_{ss \, u_a})/(S \, H_s)$ should not be a function of $H_s$. Equation 4.15 reduces to:

$$\frac{C_{ss \, u_a}}{S \, H_s} = g_7 \left( \text{Re}, C_f, L, W, H, L_{int}, W_{int} \right).$$  \hspace{1cm} (4.16)

The geometric parameters on the right hand side of Equation 4.16 must be further non-dimensionalized by one another to make the equation dimensionally correct. The choice of length scale to non-dimensionalize the other length scales is arbitrary. One example of a dimensionally consistent equation is:

$$\frac{C_{ss \, u_a}}{S \, H_s} = g_8 \left( \text{Re}, C_f, \frac{L}{L_{int}}, \frac{W}{L_{int}}, \frac{H}{L_{int}}, \frac{W_{int}}{L_{int}} \right).$$  \hspace{1cm} (4.17)

In the proceeding chapters when analytical equations are developed, the appropriate non-dimensional length scale will be selected based on the physics of the particular problem. This will only be done when doing so improves understanding of the trends or the physics responsible for the trends. Otherwise, non-dimensional concentration trends will be presented as functions of dimensional building geometry parameters. This makes the results more accessible to urban designers and policy makers who are not accustomed to thinking in dimensionless length scales.

The results in Figure 4-5 suggest that $(C_{ss \, u_a})/(S \, H_s)$ is not a function of the Reynolds number over the range of $1.4 \times 10^6$ to $6.8 \times 10^6$ ($H_s$ is a constant in Figure 4-5). This is further confirmed by varying $W_{int}$ while fixing all other dimensionless parameters in Equation 4.17. To this end, $W_{int}$ was varied from 10-50 m while $u_a$
was fixed at 10 m/s. These simulations were meshed and simulated as previously discussed in Sections 3.1.2-3.2 and 4.1. The results are shown in Figure 4-3. The root-mean-square deviation of these results is 1.6, resulting in a coefficient of variation of root-mean-square deviation of $1.2 \cdot 10^{-2}$. This result combined with those in Figure 4-5 prove that $(C_{ss} u_a)/(S H_s)$ is independent of Reynolds number in the range of $1.4 \cdot 10^6$ to $3.4 \cdot 10^7$. Therefore, Equation 4.17 may be reduced to:

$$
\frac{C_{ss} u_a}{S H_s} = g_\delta \left( C_f, \frac{L}{L_{int}}, \frac{W}{W_{int}}, \frac{H}{H_{int}}, \frac{W_{int}}{L_{int}} \right). 
$$

\hspace{1cm} (4.18)

![Figure 4-6: $(C_{ss} u_a)/(S H_s)$ vs. Reynolds number and $W_{int}$ and for an idealized gridded neighborhood](image)

Using these results and the result found in Section 4.2, one may predict the volume-averaged steady-state concentration, $C_{ss}$, in a particular gridded neighborhood for any
release rate and any reasonable Reynolds number through the inlet based on a single simulation, so long as all geometric parameters, the wind orientation and the surface roughness are held constant. This reduces the number of simulations necessary to understand the mixing characteristics of a particular geometry, and increases the utility of every CFD simulation performed in the following chapters of this thesis.
Chapter 5

Intersection frequency

Orthogonal intersections are common in urban areas as shown in Figure 3-1. The mean flow fields in the UCL near these intersections are three-dimensional and complex [Carpentieri et al., 2009]. There is lateral mixing between the UCL volumes shown in Figure 3-7 due to flow structures caused by the presence of intersections [Soulhac et al., 2009; Tiwary et al., 2011; Hang and Li, 2010]. Additionally, intersections influence the mean and turbulent vertical velocities at roof level in the UCL which are directly related to the concentrations in the UCL volumes, as discussed in Section 3.2.

Tiwary et al. [2011] provide a review of experimental campaigns and operational models that include street intersections, and discuss the importance of this work as it relates to the exposure of pollutants to pedestrians and cyclists in urban areas. They conclude that there is a need for further investigation of the underlying fluid mechanical processes near an intersection, and that this investigation should be focused on developing an understanding of how the fluid mechanical processes affect the magnitude of the concentrations near intersections.

One operational model of note is SIRANE, which uses a box model approach to predict the concentration in the street based on the urban geometry, meteorological conditions, pollutants advected into the domain and emissions within each street [Soulhac et al., 2011]. Sensitivity analyses were carried out and the model
was compared to experimental data for realistic geometries in Soulhac et al. [2012] and Carpentieri et al. [2012]. The model performed well along the axis of the main streets, however it significantly under-predicted and over-predicted concentrations in other areas of the UCL [Tiwary et al., 2011]. SIRANE is based on empirical and semi-analytical models for the mean flow field and the turbulent fluxes at the interface of the UCL and the UBL, and these models require urban geometric inputs that are more complicated than those discussed in 4.1. This, and the advanced mathematics required to solve their model, makes it less useful to urban designers. Though it is based on physics, and may be useful in real cities, it does not leave the user with a physical understanding of how changing the length or width of a grid of buildings or city blocks affects the vertical removal of pollutants in the adjacent street canyons or in the neighborhood overall. This thesis aims to take a simpler approach, informed by CFD and fluid mechanical insight, which is to present results that are understandable to urban designers, explain the trends in these results and discuss the implications of these results on urban design.

Section 5.1 evaluates the effect of varying $L$, shown in Figure 4-1, and thereby varying the intersection frequency in the direction of the wind, on dimensionless concentrations in the UCL. Section 5.2 considers the effect of varying $W$, i.e. the intersection frequency perpendicular to the wind, on dimensionless concentrations. Variations in both $L$ and $W$ are presented in Section 5.3. The implication of these results on urban design applications are discussed in Section 5.4.

5.1 Variations in intersection frequency parallel to the wind

The domain shown in Figure 5-1 was meshed and simulated as described in Section 3.1 and was post-processed as described in Section 3.2 for a range of cases from $L = 8 - 160$ m, in increments of 8 m. The dimensionless concentration is computed for each case at both a neighborhood scale and a street canyon scale.
Transient concentration data is presented at $t = 60$ s in Section 5.1.1, and the physics responsible for the trends in this data are discussed. Steady state concentration data and relevant physics are discussed in Section 5.1.2.

### 5.1.1 Transient results and relevant physics for variations in building length

Figure 5-2 shows the variation of the dimensionless concentration, which has been bulk-averaged over the UCL, $(C u_a) / (S H_s)$, with increasing building length, $L$, after one minute of species release into the fully-developed velocity field around the repeating geometry shown in Figure 5-1. The dimensionless concentration at $t = 60$ s is approximately 30 for all values of $L$ that were simulated.

The total mass of species released into the domain after a certain amount of time has elapsed, $m(t = t_f)$, can be calculated as:

$$m(t = t_f) = \int_{t=0}^{t=t_f} S dV_s dt,$$

(5.1)

where $t_f$ is the amount of time that has elapsed. If none of the species has been removed from the UCL to the UBL after $t_f$ the dimensionless concentration in the
Figure 5-2: \( \frac{(C_{ua})}{(S_{Hs})} \) vs. \( L \) at \( t = 60 \) s, averaged over the UCL

UCL is:

\[
\left( \frac{C_{ua}}{S_{Hs}} \right)_{\text{Lat}} = \frac{m(t = t_f) \ u_a}{S_{Hs} \ V_b}, \tag{5.2}
\]

where \( V_b \) is the volume of the UCL and \( \left( \frac{(C_{ua})}{(S_{Hs})} \right)_{\text{Lat}} \) represents the lateral dimensionless concentration. If \( \frac{(C_{ua})}{(S_{Hs})} = \left( \frac{(C_{ua})}{(S_{Hs})} \right)_{\text{Lat}} \), none of the species released into the UCL has been vertically removed to the UBL, however it may have been advected laterally and vertically up to \( z/H < 1 \) within the UCL. Species that has been advected from one UCL volume defined in Figure 3-7 and into another are considered to have been mixed laterally (as opposed to being vertically mixed into the UBL). Integrating Equation 5.1, and substituting it into Equation 5.2 results in:

\[
\left( \frac{C_{ua}}{S_{Hs}} \right)_{\text{Lat}} = \frac{V_s t_f \ u_a}{H_s V_b}. \tag{5.3}
\]
For the geometry in Figure 5-1, Equation 5.3 can be rewritten as:

\[
\left( \frac{C \ u_a}{S \ H_s} \right)_\text{Lat} = \frac{(L \ W_{int} + W \ L_{int} + W_{int} L_{int}) \ H_a \ t_f \ u_a}{(L \ W_{int} + W \ L_{int} + W_{int} L_{int}) \ H_s H} = \frac{t_f \ u_a}{H}.
\]  

(5.4)

Plugging in the values used to generate Figure 5-2 \((t_f = 60 \ s, \ u_a = 10 \ m/s \ \text{and} \ H = 20 \ m)\), \(\left( \frac{C \ u_a}{S \ H_s} \right)_\text{Lat} = 30\), approximately equal to the results in Figure 5-2. This means that after one minute of species release in these cases nearly all of the released species remains in the UCL.

To understand how the species has been advected within the UCL, the data in Figure 5-2 is presented at a street canyon scale in Figure 5-3. This shows how the dimensionless concentration is distributed among the relevant UCL volumes defined in Figure 3-7. Because this data is for the situation where almost all of the released species remains in the UCL, the trends in Figure 5-3 are due to lateral mixing between the UCL volumes rather than differences in the vertical mixing ability of the different volumes. Understanding the physics responsible for the trends in Figure 5-3 is possible by first understanding the physics of the flow field around a well understood street canyon geometry, and then incrementally increasing the complexity of the geometry.

First consider the flow in the well-studied case of traverse skimming flow over a two-dimensional street canyon, reviewed briefly in Section 4.1 of Britter and Hanna [2003] and reviewed in depth in Li et al. [2006]. Figure 5-4(a) shows where this sort of flow field may exist in an orthogonally gridded neighborhood, i.e. in sections of cross canyons that are not near intersections. The flow in the canyon is driven by a momentum exchange between the air above the street canyon and the air in the street canyon, and the flow field is characterized by one or more vortices or recirculation regions in the \(x,z\)-plane, shown schematically in Figure 5-4(b). The recirculation region nearest the top of the street canyon, hereafter referred to as the primary recirculation region or primary vortex, is characterized by having the largest velocities. The red line with an arrow shows the direction of the primary vortex in these street canyons. The blue \(\otimes\) represents an example vortex line associated with the primary vortex point into the page, meaning that it is aligned with the \(y\)-axis and
that the vorticity is in the $y$-direction. At large enough Reynolds numbers the vertical dimension of the primary vortex is in the range of $L_{int} - 2L_{int}$ for street canyons with aspect ratios $(H/L_{int})$ of two [Li et al., 2005].

Figure 5-3: $(C_{u_a}) / (S \theta)$ vs. $L$ at $t = 60$ s, averaged over UCL volumes

Figure 5-4: Idealized two-dimensional street canyon

Figure 5-5 shows the surface streamlines projected onto an $x,z$-plane taken at $y/W_{int} = 2.5$ for the $L = 88$ m domain from Figure 5-1. Because of the more complex geometry considered, the shape of the recirculation region is not the same as the two-
dimensional case studied by Li et al. [2005]. Based on the direction of the normalized vertical velocity, $w/u_a$, it is apparent that the vorticity of the primary recirculation region is still in the positive $y$-direction for the cross canyons in the orthogonally gridded neighborhood considered.

Figure 5-5: Surface streamlines projected onto an $x,z$-plane taken at $y/W_{int} = 2.5$ for the $L = 88$ m case, colored by the non-dimensional vertical velocity, $w/u_a$.

With the characteristics of the flow in the two-dimensional traverse-flow case in mind, one may predict the shape of some of the vortex lines in the case of an orthogonal intersection of two street canyons with the incident wind aligned with one of the street canyons. Consider a simplified case where the shear stress applied to the fluid by the ground and the building façades aligned with the wind is initially ignored, shown in Figure 5-6. At the intersection the cross canyon experiences the same incident flow as the example in Figure 5-4, but in the $x,y$-plane rather than the $x,z$-plane. The blue line is an example vortex line for this idealized intersection. The red lines show the direction of the flow in the recirculation zones in the cross canyon. This phenomenon has also been documented by Soulhac et al. [2009].

Figure 5-7 shows a more realistic vertical profile of the horizontal wind in the street canyon aligned with the wind. The fluid will separate off the upper downwind corner of the upwind building creating an area of low pressure behind that corner. This stretches the vortex lines towards that corner, shown schematically by the blue arrow in Figure 5-7. The stretching of these lines means that there will be an $x$-direction
component of the vortex lines near the intersection. This will tilt the idealized recirculation zone near the intersection, shown schematically with the small red arrow in Figure 5-7.

Figure 5-6: An idealized three-dimensional intersection of two street canyons

Figure 5-7: A more realistic three-dimensional intersection of two street canyons

Consider a section cut midway through the cross canyon as in Figure 5-8(a). Figure 5-8(b) shows a $y,z$-plane projection of the recirculation zone. The red lines schematically show the direction of the $x$-vorticity. The black arrows explain the effect of this vorticity on the mean flow field. Fluid in the lower part of the street will flow from the cross canyon to the intersection and fluid in the upper part of the street will flow from the intersection to the cross canyon. This flow in the $y$-direction was also documented for a non-periodic case studies of gridded buildings.
Hang and Li [2010]. The black to white gradient in Figure 5-8(b) represents the near-ground volume source release of the species. When the species is concentrated near the ground, which will be the case at small times, this $x$-vorticity will cause fluid with much greater species concentration to leave the cross canyon and enter the intersection and fluid with lesser species concentration to leave the intersection and enter the cross canyon. Because the incident wind is in the $x$-direction, the higher concentration fluid that was transported into the intersection will be advected into the long canyon aligned with the wind. The streamlines near the intersection are shown in plan view at various heights for the $L = 88$ m case in Figure 5-9. They are colored by $v/u_a$, the normalized velocity in the $y$-direction to clearly show if fluid is moving into or out of the cross canyon. At $z/H = 0.1$ and 0.2 the fluid is moving from the cross canyon into the intersection, and then directly into the long canyon. At these heights nearly all of the fluid from in the long canyon is coming directly from the cross canyon. There are near-ground recirculation regions near the lower upwind corners of the downwind buildings of each intersection due to flow separation. $z/H = 0.3$ is the transition height for this case, where there is minimal mean flow across the interface between the cross canyon and the intersection. This case shows how the recirculation region near the intersection is similar to the two-dimensional canyon cases reviewed by Li et al. [2006]. From $z/H = 0.4$ to 0.8 there is mean flow from the edges of the long canyon to the cross canyons. The fluid in the center of the long canyon at these heights flows in the direction of the wind, through the intersection and into the next long canyon. The bending of the vortex lines shown schematically in Figure 5-7 is evidenced by the center of the recirculation moving in the negative $x$-direction as $z/H$ increases. At $z/H = 0.95$ most of the fluid is moving in the same direction as the incident wind.

Figure 5-10(a) depicts a $y$-axis facing section view of portions of some of the three-dimensional streamlines for the $L = 88$ m case to show the structure of the recirculation region shown schematically in Figure 5-7 and in plan in Figure 5-9. For ease of understanding the streamlines are hidden after a certain distance along the cross canyon to isolate the complex flow structure near the intersection. The
Figure 5-8: A more realistic three-dimensional intersection of two street canyons, section B-B'.

Streamlines are colored with $v/u_a$ to show if a particular streamline is moving into or out of the intersection. The bending of the vortex lines towards the upper downwind corner of the upwind building is evident in Figure 5-10(a) by the shape of the tightly wound streamlines in the center of the recirculation region. It is also evident that there is an $x$-component of vorticity. Figure 5-10(b) shows an orthographic perspective view of the flow structure which clearly displays the $x$-vorticity in the recirculation zone and the mean flows into and out of the intersection.

To understand how this structure affects the concentration in long canyons, consider the schematic drawing of the domain shown in Figure 5-11. $C_a$ represents the concentration in the lower section of the long canyon before it has been affected by the species flux from the cross canyons and $C_b$ represents the concentration in the cross canyons that is transferred to the long canyons via the mean flow.

The total concentration in the long canyons, $C_{a,\text{total}}$, may be approximated analytically as

$$C_{a,\text{total}} = \frac{C_b (2L_{int}^2) + C_a (L W_{int})}{L W_{int}},$$

assuming that the amount of species transferred from the cross canyons scales as the size of the recirculation zone and that the recirculation zone has an aspect ratio of approximately unity. This aspect ratio is consistent with the simulations in this thesis as well as the work discussed by Tiwary et al. [2011].
Figure 5-9: Plan view of the streamlines at the intersection of the $L = 88$ m case at various heights
Figure 5-10: Three-dimensional streamlines showing the recirculation region near the intersection for the $L = 88$ m case, (a) Section view facing positive $y$-direction, (b) Three-dimensional orthographic projection
If $C_a$ and $C_b$ are assumed to be constant for all values of $L$ at small enough times, Equation 5.5 is linear and can be rewritten as:

$$C_{a,\text{total}} = C_b \left( \frac{2L_{\text{int}}^2}{L W_{\text{int}}} \right) + C_a.$$  \hspace{1cm} (5.6)

This means that the concentration in the long canyons should vary linearly with $2L_{\text{int}}^2/(L W_{\text{int}})$ at small enough times. The concentrations in the UCL volumes from Figure 5-3 are displayed against $2L_{\text{int}}^2/(L W_{\text{int}})$ in Figure 5-12. The dimensionless concentration in the long canyons appears to be linear, with the exception of the two cases with the smallest values of $L$.

These cases with smaller values of $L$ have a more complicated flow field with reverse flow in the long canyons, which explains their deviation from Equation 5.6. First, consider the simpler case of $L = 88$ m – flow fields shown in Figure 5-13. The streamlines are colored by the normalized $x$-velocity, $u/u_a$, to more easily distinguish reverse flow relative to the direction of the wind. A section view of the streamlines through the center of the long canyon, displayed in Figure 5-13(a), shows that all of the fluid is moving in the direction of the wind. Figure 5-13(b), a section view nearer the wall of the long canyon at $y/W_{\text{int}} = 0.4$, shows the scale of the small recirculation zone, which interrupts only a small portion of the streamlines moving from the upwind long canyon to the intersection and then to the downwind long...
Figure 5-12: $(C' u_a) / (S H_s)$ vs. $2L_{int}^2 / (L W_{int})$ at $t = 60$ s, averaged over UCL volumes.

canyon. The is shown in plan at $z/H = 0.1$ in Figure 5-13(c). Figure 5-13(d) shows a three-dimensional streamline which captures the shape and scale of the recirculation caused by the separation of the fluid off the lower upwind corner of the downwind building.

Streamlines for a case with a smaller value of $L$, $L = 16$ m, are shown in Figure 5-14. Streamlines projected onto a plane through the center of the long canyon, displayed in Figure 5-14(a), show that there is significant flow in the negative $x$-direction in the downwind section of these shorter long canyons. At a great enough value of $z/H$ the flow is eventually realigned with the incident wind direction. Cases with a smaller $L$ have a larger surface area of rough walls per unit plan area which act as a greater shear force on bulk fluid flowing through the domain. This causes the average horizontal velocity to be zero at some height in the street canyon (known as the displacement height in the log-law formula for the vertical profile of horizontal
Figure 5-13: Streamlines for the $L = 88$ m case colored by $u/u_a$, (a) Section view at $y/W_{int} = 0$, (b) Section view at $y/W_{int} = 0.4$, (c) Plan view at $z/H = 0.1$, (d) Orthographic view of three-dimensional streamline showing recirculation zone

wind over a rough surface). This is unlike the cases with longer values of $L$, as evidenced by the surface streamlines projected onto a plane at $z/H = 0.1$ in Figure 5-13(c), which only have an average velocity of zero at the no-slip condition at the ground. Near ground bulk flow in the wind direction, like that shown in Figure 5-13(c), is absent from these cases with smaller values of $L$ due to increased shear on the fluid from the increase in the rough surfaces. Because there is no average flow in the $x$-direction, which would transfer positive $x$-momentum to the fluid below, the flow in the $y$-direction from the cross canyons into the intersections behaves more like sudden expansions rather than like the flow fields in Figure 5-13(c). Because the intersections are so close together, the sudden expansion flow fields create the recirculation regions shown in Figure 5-14(b). These recirculation regions prevent the species flux from the cross canyon from going directly into the downwind long canyon. The near-zero $x$-velocity in the intersections in these cases will lead to increased concentrations in the
intersections because the fluid is not flowing directly in the $x$-direction along the long canyons as in cases with larger values of $L$. This explains the non-linearity in the long canyon dimensionless concentration data as well as the increased concentration in the intersections for small values of $L$ in Figures 5-3 and 5-12. The three-dimensional streamlines showing the shape and size of the recirculation regions are shown for the negative-$y$ half of the long canyon in Figure 5-14(c). These recirculation regions will also affect the steady state concentrations, discussed in Section 5.1.2.

![Streamlines for the $L = 16$ m case colored by $u/u_a$, (a) Section view at $y/W_{int} = 0$, (b) Plan view at $z/H = 0.1$, (c) Orthographic view of three-dimensional streamlines showing recirculation zones](image)

The trend in the intersection data in Figure 5-12 is partially explained by Figure 5-13(c). Because $u/u_a$ is similar in magnitude and direction near the ground in the cases with larger $L$, evidenced by straight streamlines across the long canyon, the intersections will have similar concentrations to the long canyons.
The intersections have concentrations similar to the cross canyons for the cases where \( L = 24 - 56 \) m, as shown in Figure 5-3. These cases have flow fields that show aspects of both the \( L = 88 \) m case and the \( L = 16 \) m case. Streamlines for a case showing the transition between the \( L = 88 \) m case and the \( L = 16 \) m case are presented in Figure 5-15, the case where \( L = 40 \) m. Figure 5-15(a) shows the surface streamlines projected onto the \( x,z \)-plane in the center of the long canyon. There is some reverse flow in this case, colored blue, however the extents of the reverse flow is less than in the \( L = 16 \) m case. The surface streamlines projected onto the \( x,z \)-plane in Figure 5-15(b) show the two-dimensional structure of the recirculation regions in the long canyon. The sudden expansion effect is shown in Figure 5-15(c), however there is enough momentum in the direction of the wind in the long canyon to prevent this effect downwind of the intersection. Downwind of the intersection the long canyon behaves more like the \( L = 88 \) m case, with the distinctive separation off the lower upwind corner of the downwind building. Upwind of the intersection this case behaves more like a sudden expansion with reverse flow like the \( L = 16 \) m case. This recirculation region blocks the upwind fluid moving in the \( x \)-direction, causing it to recirculate and move vertically into the bulk flow. Because the fluid is moving from the cross canyon through the intersection to the long canyon with a large positive value of \( u/u_a \) relative to the near ground velocity shown in Figure 5-15(c) and because the recirculation region upwind of the intersection prevents fluid from entering the intersection from the upwind long canyon near the ground, the intersection concentration will be similar to the cross canyon for these transition values of \( L \). The recirculation region downwind of the intersection and how it interacts with the three-dimensional vortex in Figure 5-10 is shown in Figure 5-15(d). The recirculation region upwind of the intersection and its relationship to the bulk flow is shown in Figure 5-15(e).

As previously explained, because of the near-zero \( x \)-velocity in the intersections for the \( L = 8 - 16 \) m which show characteristics similar to a sudden expansion, there will be higher concentrations in the intersections relative to the cross canyons in these cases, as seen in Figure 5-3.
Figure 5-15: Streamlines for the $L = 40$ m case colored by $u/u_a$; (a) Section view at $y/W_{int} = 0$, (b) Section view at $y/W_{int} = 0.3$, (c) Plan view at $z/H = 0.15$, (d) Orthographic view of three-dimensional streamlines showing recirculation zone downwind of the intersection, (e) Orthographic view of three-dimensional streamlines showing recirculation zone upwind of the intersection
The concentration in the cross canyons is not a function of the changing length of the building, as shown in Figure 5-3. This fits with the assumption that regardless of \( L \), the same amount of species is transferred out of the cross canyon near the ground by the three-dimensional vortex as shown schematically in Figure 5-11 and as approximated by Equation 5.5. The urban design implications of the results shown in Figure 5-3 will be discussed in Section 5.4.

5.1.2 Steady state results and relevant physics for variations in building length

The steady state dimensionless concentration, bulk-averaged over the UCL, is plotted against building length in Figure 5-16 for the domain shown in Figure 5-1. \( C_{ss} \) represents the steady-state concentration averaged over a particular volume. As \( L \) increases the average dimensionless concentration in the neighborhood increases. The trends in Figure 5-16 could be fit to two straight lines of different slopes which meet at approximately \( L = 64 \) m.

The trend in Figure 5-16 can be understood by first considering the steady state dimensionless concentrations averaged over the relevant UCL volumes, shown in Figure 5-17.

At steady state it is useful to compare the magnitudes of the dimensionless concentrations in the UCL volumes relative to their idealized counterparts as a baseline. To this end, infinitely long street canyons oriented parallel and perpendicular to the wind were modeled after the geometry displayed in Figure 5-1, as shown in Figure 5-18. The domains were meshed and the fully-developed flow fields and species calculations were simulated using the setup described in Section 3.1. The results were post-processed using the techniques described in Section 3.2. The resulting dimensionless concentrations were \( ((C_{ss} u_a)/(S H_s))_{long,ideal} = 288 \) and \( ((C_{ss} u_a)/(S H_s))_{cross,ideal} = 58.5 \) for the canyon aligned with the wind and the canyon perpendicular to the wind, respectively. An infinitely long street canyon parallel to the wind has a higher concentration."
Figure 5-16: \( (C_{ss\, u_a}) / (S\, H_s) \) vs. \( L \) at steady state, averaged over the UCL

at steady state than any of the long canyons in Figure 5-17, while the infinite cross canyon has a lower concentration than the cross canyons in this study.

The discrepancies between the dimensionless concentrations in the idealized cases and those shown in Figure 5-17 are due to the presence of intersections. The effect of intersections can be quantified at a neighborhood scale by comparing the steady state neighborhood concentration data in Figure 5-16 to an idealized neighborhood concentration, \( ( (C_{ss\, u_a}) / (S\, H_s) )_{\text{ideal}} \), based on the infinitely long street canyons. This can be done by computing a weighted average of the two idealized results as:

\[
\left( \frac{C_{ss\, u_a}}{S\, H_s} \right)_{\text{ideal}} = \frac{\left( \frac{C_{ss\, u_a}}{S\, H_s} \right)_{\text{long, ideal}} V_{\text{long}} + \left( \frac{C_{ss\, u_a}}{S\, H_s} \right)_{\text{cross, ideal}} V_{\text{cross}} + \left( \frac{C_{ss\, u_a}}{S\, H_s} \right)_{\text{int, ideal}} V_{\text{int}}}{V_{\text{long}} + V_{\text{cross}} + V_{\text{int}}}, \tag{5.7}
\]

where \( V_{\text{long}}, V_{\text{cross}} \) and \( V_{\text{int}} \) represent the volumes of the long canyons, cross canyons and intersections, respectively. The dimensionless concentrations for the intersections are somewhere between that of the long canyons and that of the cross canyons.
Figure 5-17: \( \left( C_{ss} u_a \right) / \left( S H_s \right) \) vs. \( L \) at steady state, averaged over UCL volumes

for all values of \( L \) in Figure 5-17, thus \( \left( \left( C_{ss} u_a \right) / \left( S H_s \right) \right)_{ideal} \) is computed for two cases to show the range of possibilities for each value of \( L \): Case 1 – Best case, where \( \left( \left( C_{ss} u_a \right) / \left( S H_s \right) \right)_{int,ideal} = \left( \left( C_{ss} u_a \right) / \left( S H_s \right) \right)_{cross,ideal} \) and Case 2 – Worst case, \( \left( \left( C_{ss} u_a \right) / \left( S H_s \right) \right)_{int,ideal} = \left( \left( C_{ss} u_a \right) / \left( S H_s \right) \right)_{long,ideal} \). These cases are plotted with the simulated neighborhood results in Figure 5-19. The Case 1 and Case 2 data in Figure 5-19 show that when \( L \geq 40 \) m the presence of intersections reduces the dimensionless concentrations in the neighborhoods when compared to an idealized case of infinitely long street canyons. The neighborhoods with \( L < 40 \) m have larger dimensionless concentrations than one or more of the idealized cases shown in Figure 5-19 because of lateral mixing between the UCL volumes (specifically, a systematic increase in cross canyon concentration due to lateral mixing), discussed later in this section. Though the neighborhood scale data is greater than the ideal cases in the \( L \leq 40 \) m cases, the average dimensionless concentrations in the long canyons will be lower, leading to a more well-mixed neighborhood than the ideal cases.
To understand the trends at a street canyon scale, i.e. the trends in Figure 5-17, one must consider the mean flow fields in these domains. The dimensionless $x$-velocity averaged over the long canyons, $u_c/u_a$, is presented in Figure 5-20 for the range of $L$ simulated. In general, $u_c/u_a$ increases as $L$ increases. This is because the cases with smaller $L$ have a larger surface area of rough walls per unit plan area which provide a greater shear force on the fluid in the domain. This causes an increase in displacement height, which results in the average velocity in the direction of the wind to be zero at a value of $z > 0$ m.

The magnitude of vertical turbulent momentum exchange between the UBL and the UCL will scale as the difference between the average velocity in the UBL and the average velocity in the UCL, $(u_a - u_c)$ [Hall et al., 2012]. For a particular geometry,

$$\alpha = \frac{u_c}{u_a - u_c},$$

(5.8)

where $\alpha$ is an exchange coefficient, which is a constant for a given geometry and $u_e$ is the turbulent exchange velocity. Based on Equations 3.28 and 3.37 and the reasoning in Section 3.2, the steady state concentration bulk averaged over a particular periodic volume will be:

$$C_{ss} = \frac{V_s S}{A u},$$

(5.9)

where $A$ is the plan area of the UCL and UBL interface and $u$ is velocity responsible for transporting the species vertically across the interface. For the cases in this chapter,
Figure 5-19: \( \frac{(C_{ss} u_a)}{(S H_s)} \) vs. \( L \) at steady state, averaged over the UCL with idealized cases

\( V_s/A = H_s \). Assuming all of the species transport across the interface of the infinitely long canyon parallel to the wind is due to vertical turbulent diffusion rather than mean flows \((u = u_c)\) and using Equation 5.8, Equation 5.9 becomes:

\[
C_{ss} = \frac{H_s S}{\alpha (u_a - u_c)}. \tag{5.10}
\]

This can be written in terms of the dimensionless concentration:

\[
\left( \frac{C_{ss} u_a}{S H_s} \right)_{\text{long, ideal}} = \frac{u_a}{\alpha (u_a - u_c)}. \tag{5.11}
\]

For the infinitely long street canyon aligned with the wind shown in Figure 5-18, \( u_c = 2.77 \text{ m/s} \). This results in an exchange coefficient of \( \alpha = 4.80 \cdot 10^{-3} \). Using this value of \( \alpha \), the expected steady state dimensionless concentration, assuming only turbulent exchange between the UCL and the UBL, \( ((C_{ss} u_a) / (S H_s))_{\text{long, T}} \), may be
Figure 5-20: \((u_c/u_a)_{long}\) vs. \(L\), averaged over the long canyons

computed from the data in Figure 5-20 and Equation 5.11. The results are plotted in Figure 5-21: the blue circles are the same long canyon data as that of Figure 5-17, the black line represents the baseline value for the infinitely long street canyon, and the black “x”’s represent \(((C_{ss}/, u_a)/(S H_s))_{long,T}\). The trend in the simulated data is similar to the \(((C_{ss}/, u_a)/(S H_s))_{long,T}\) values for \(L \geq 64\) m, however there is still a large discrepancy between these two data sets. This can be explained by considering lateral mixing within the UCL and vertical mean flows, phenomena not present in the infinitely long street canyon.

The intersections allow lateral mixing between the cross canyons and the long canyons as discussed in Section 5.1.1 and shown in Figures 5-9 and 5-10. At \(t = 60\) s this lateral exchange reduces dimensionless concentrations in the cross canyons, and increases dimensionless concentrations in the long canyons. At steady state, however, this lateral effect causes the discrepancy between the concentration in idealized cross canyon and the cross canyon data in Figure 5-17. This is because the mean flow
Figure 5-21: \( \left( \frac{C_{zz} u_a}{S H_s} \right)_{long} \) vs. \( L \) at steady state, turbulent effects of species in the upper part of the three-dimensional vortex in Figure 5-10 moves from the upwind long canyon into the downwind cross canyon. It is important to note the following points: (1) this effect occurs over a greater vertical distance than the cross canyon to long canyon motion in the lower part of the three-dimensional vortex, (2) the upper air is moving at a higher velocity than the lower air, and (3) after long enough times the dimensionless concentration in the upper part of the long canyon will be more similar to the near-ground air due to vertical advection and vertical turbulent diffusion of the species. This is shown for the \( L = 144 \text{ m} \) case in Figure 5-22. Figure 5-22(a) shows the transient concentration contours on an \( x,z \)-plane along the center of the long canyon at \( t = 60 \text{ s} \). This is in contrast to the more vertically mixed contours shown in Figure 5-22(b) for \( t = 960 \text{ s} \). Therefore, the steady state species fluxes due to the three-dimensional vortex lead to an increase in dimensionless concentration in the cross canyons and a decrease in the dimensionless concentration in the long canyons. This is the opposite of the effect discovered in
Figure 5-22: Concentration data for the $L = 144$ m case at (a) $t = 60$ s, and (b) $t = 960$ s
Section 5.1.1. At the scale of UCL volumes, this makes the neighborhoods more well mixed in that the magnitude of dimensionless concentration averaged over the cross canyons is closer to that of the long canyons than in the idealized case. Because this mixing is lateral, it will affect the spatial distribution of the species within the UCL, thereby affecting the dimensionless concentration in the UCL volumes. The effect of this lateral species mixing on the dimensionless concentrations in the long canyons may be quantified assuming that all of the discrepancy between the cross canyon data and the ideal cross canyon data is due to this effect. The cases considered were limited to $L \geq 64$ m because these cases are all characterized by flow fields in the long canyon like those shown in Figure 5-13. The other cases are complicated by large portions of $V_{long}$ having reverse flow and recirculation zones near the ground. The steady state dimensionless concentration in the long canyons after accounting for turbulent and lateral effects, $\left( \frac{C_{ss}}{u_a} / \left( \frac{S H_s}{T} \right) \right)_{long,LT}$, may be calculated as:

$$
\left( \frac{C_{ss}}{u_a} / \left( \frac{S H_s}{T} \right) \right)_{long,LT} = \frac{\left( \frac{C_{ss}}{u_a} / \left( \frac{S H_s}{T} \right) \right)_{cross,LT} - \left( \frac{C_{ss}}{u_a} / \left( \frac{S H_s}{T} \right) \right)_{cross,ideal}}{V_{long} V_{cross}}, \quad (5.12)
$$

where $\left( \frac{C_{ss}}{u_a} / \left( \frac{S H_s}{T} \right) \right)_{cross,LT}$ is the cross canyon simulation data shown with red squares in Figure 5-17. This cross canyon data is assumed to differ from the ideal cross canyon data only because of lateral effects. The results from Equation 5.12 are shown with black diamonds, along with the results from Figure 5-21 in Figure 5-23. The slope of the $\left( \frac{C_{ss}}{u_a} / \left( \frac{S H_s}{T} \right) \right)_{long,LT}$ data is even more similar to the simulated neighborhood data, $\left( \frac{C_{ss}}{u_a} / \left( \frac{S H_s}{T} \right) \right)_{long}$ (blues circles), than the $\left( \frac{C_{ss}}{u_a} / \left( \frac{S H_s}{T} \right) \right)_{long,T}$ data. The discrepancy between the black diamond data and the blue circle data is due to changes in the vertical mean flow in the simulated neighborhood cases due to the presence of intersections. The assumption that the cross canyon data differs from the ideal cross canyon due to only lateral effects also assumes that there will be no changes in the vertical mean flow out of the cross canyons due to the presence of intersections. Though this is not the case, the changes in mean flow will be approximately equal for all values of $L$ because the mean flow field is
This means that the black diamond data in Figure 5-23 may be translated greater than is shown, however the shape will be the same. This assumption, though somewhat inaccurate, gives the reader a sense of the shape of the trend, and shows that for \( L \geq 64 \) m the contribution of mean vertical advection to reducing the concentration in the long canyons is not strongly related to \( L \), i.e. the distance between the blue circles and the black diamonds is approximately constant. The contribution of lateral advection towards reducing the concentration in the long canyons decreases as \( L \) increases.

The intersections increase the mean absolute value of vertical velocities in the long canyons in comparison to the infinitely long case. This is because the bulk flow in the long canyons must go around the separation zone near the lower upwind corner of the downwind building, shown in Figures 5-13(b)-(d). The positive normal vertical velocity, \( w/u_a \), due to the separation zone for the \( L = 144 \) m case is highlighted in red in the streamlines in Figure 5-24. The blue represents the negative component.
of the normalized vertical velocity, which is due to reattachment of the flow after the recirculation zone. This negative vertical velocity is also necessary for conservation of mass, assuming the inlet and outlet long canyon velocities are equal. These enhanced vertical mean flows, relative to the infinite case, will reduce the dimensionless concentrations in the long canyons in comparison to the infinite case. The approximate contributions of the vertical turbulent diffusion, lateral advection and mean vertical advection towards removing species from the long canyons are shown schematically in Figure 5-25. While there is no removal of species due to lateral effects in the ideal case, and the mean effects are negligible, the turbulent flux of species is responsible for removing as much species as is generated at each time step at steady state. This means that the blue shaded area in Figure 5-25 quantifies the amount that turbulent effects reduce concentrations above and beyond that of the ideal canyon case, not the total effect of turbulence on the magnitude of the concentration.

Figure 5-24: Streamlines colored by $w/u_a$ for the $L = 144$ m case on an $x,z$-plane at $y/W_{int} = 0$

The cross canyon dimensionless concentration data in Figure 5-17 is mostly flat in comparison to the trends for the long canyons and intersections. This is because regardless of $L$, the cross canyon concentrations are affected by the lateral mixing between the long canyons and cross canyons due to the same phenomenon, the three-dimensional vortex. Because the mean flow behavior is similar for all cases (out of the cross canyons for small $z/H$ and into the cross canyons for large $z/H$, as shown
Additional vertical turbulent diffusion
Lateral advection
Mean vertical advection
○ \((C_{ss} u_a) / (S H_s)_{long}\)
- \((C_{ss} u_a) / (S H_s)_{long,ideal}\)
\(\times\) \((C_{ss} u_a) / (S H_s)_{long, T}\)
\(\Diamond\) \((C_{ss} u_a) / (S H_s)_{long, LT}\)

Figure 5-25: \((C_{ss} u_a) / (S H_s)_{long}\) vs. \(L\) at steady state, turbulent, lateral and mean effects

in Figure 5-9), the turbulent vertical diffusion of species out of the cross canyons will not be greatly affected by the presence of intersections (the flow field in much of the distance along the cross canyons is still that shown in Figure 5-5). Therefore the cross canyon concentration will be nearly constant for variations in \(L\). There is a slight positive linear slope in the cross canyon data for \(L \geq 64\) m. As discussed to previously, this is due to the long canyons having greater concentrations as \(L\) increases due to reductions in turbulent mixing. This increase in concentration in the long canyons with increasing \(L\) affects the cross canyons to some extent because the species flux from long canyon to cross canyon due to the upper part of the three-dimensional vortex will be greater in magnitude as \(L\) increases.

The intersections in the \(L \geq 64\) m cases behave more like long canyons than cross canyons because of the mean flow fields, as discussed in Section 5.1.1.

The cases where \(L < 64\) m are characterized by near-ground recirculation regions that cover much of the lower volume of the long canyon (from \(z/H = 0\) to \(z/H = 0.15\)-
0.35). These regions are characterized by higher concentrations resulting in the trend seen in the long canyons in Figure 5-17. Because this data is greater than if it followed the trend of the long canyon data for $L \geq 64$ m, the cross canyon concentrations are also greater due to the previously discussed lateral effects. The intersections behave more like the cross canyons for $L < 64$ m for because of the recirculation in the mean flow field, discussed in Section 5.1.1.

Figure 5-26 shows the steady state dimensionless concentration data as it varies with $L$ at pedestrian height. In this thesis, pedestrian height will refer to data averaged over the lowest 2 m of the domain. The data near pedestrian height is expected to be larger in magnitude than the entire UCL data because it is closer to the source, on average. For the $L \geq 64$ m cases, the long canyon data is approximately a factor of 2 greater than when considering the entire UCL volume (as in Figure 5-17). The cross canyon data is in these cases is only a factor of about 1.2–1.4 greater than the Figure 5-17 data. The larger increase in the long canyon data is likely due to the near ground effect of the three-dimensional vortex, which transports species from the cross canyon to the long canyon, i.e. the lower part of the lateral effect has a greater impact on the pedestrian data than the upper part of the lateral effect. The intersection data behaves as expected based on previous discussion.

For $L < 64$ m, the effect of recirculation zones on the concentration data in the long canyons is enhanced because the pedestrian data is gathered in the recirculation zones. Because these zones are characterized by large concentrations, the large dimensionless concentrations in the long canyons makes sense. The intersection data and cross canyon data make sense when considering that there will be lateral advection between these volumes and the shorter long canyons, which are characterized by recirculation zones encompassing most of the near ground volume.

The implications of the variation in the steady state dimensionless concentration data with building length, shown in Figures 5-16, 5-17 and 5-26, on urban design applications will be discussed in Section 5.4.
5.2 Variations in intersection frequency perpendicular to the wind

The domain in Figure 5-27 was meshed, simulated and post-processed in accordance with Sections 3.1 and 3.2 for the range of $W = 8$–160 m in increments of 8 m. The dimensionless concentration is computed for each of these cases at a neighborhood scale and at a street canyon scale.

Transient concentration data, taken at $t = 60$ s, and the physics responsible for the trends in this data are presented in Section 5.2.1. The steady state concentration data is presented in Section 5.2.2, and the flow phenomena responsible for the trends in this data are discussed.
5.2.1 Transient results and relevant physics for variations in building width

Figure 5-28 displays how the dimensionless concentration averaged over the UCL, \((C u_a)/(S H_s)\), varies with changes in the building width, \(W\), for the domain shown in Figure 5-27. These results were taken at \(t = 60\) s. As in Section 5.1.1, the dimensionless concentration is approximately 30 for the values of \(W\) that were simulated.

The results from Equations 5.1–5.4 apply to variations in \(W\) as well, thus

\[
\left( \frac{C u_a}{S H_s} \right)_{lat} = \frac{t_f u_a}{H}. \tag{5.13}
\]

Using the values from Figure 5-27 and the simulation setup discussed in Section 3.1, \((C u_a)/(S H_s)_{lat} = 30\). This is approximately equal to the results in Figure 5-28 which means almost all of the species that has been released by the near ground volume source remains in the UCL at \(t = 60\) s. Though most of the species has not been vertically removed to the UBL, it has been laterally advected within the UCL. This is quantified by the dimensionless concentration in the UCL volumes, presented in Figure 5-29. The trends in this street canyon scale data can be explained by the
physics of the flow field, which is similar to the flow field described in Section 5.1.1 in that the three-dimensional vortex from Figure 5-10 is present at each intersection.

Figure 5-30 schematically depicts the effect of the three-dimensional vortex near the ground on the domain in Figure 5-27. $C_c$ represents the concentration in the lower section of the cross canyon in the areas that are affected by the three-dimensional vortex. As in Section 5.1, the aspect ratio of this area is assumed to be unity and much of the species at $t = 60$ s is assumed to be in the lower part of the UCL, shown for the $L = 144$ m case in Figure 5-22(a). $C_d$ represents the concentration in the section of the cross canyon that is not directly affected by the three-dimensional vortex.

The total concentration in the cross canyons, $C_{c\text{,total}}$, is approximated analytically as

$$C_{c\text{,total}} = \frac{C_c (2 L_{int}^2) + C_d (W L_{int} - 2 L_{int}^2)}{W L_{int}}. \quad (5.14)$$
Assuming $C_c$ and $C_d$ are constant at small times for all values of $W$, Equation 5.14 may be rewritten as:

$$C_{cd, total} = (C_c - C_d) \left( \frac{2L_{int}}{W} \right) + C_d. \quad (5.15)$$

Therefore, the concentration in the cross canyons is expected to vary linearly with $2L_{int}/W$ at small times. Because the three-dimensional vortex acts to remove the species from the cross canyons, $C_c$ is predicted to be less than $C_d$, therefore the slope of the line should be negative. The dimensionless concentrations shown in Figure 5-29 are displayed as they vary with $2L_{int}/W$ in Figure 5-31.

The concentrations in the cross canyons decrease linearly with the exception of the two cases with the smallest values of $W$. If the straight line formed by this data were to continue as $2L_{int}/W$ increased, it would appear to cross the $x$-axis at approximately unity. This is the case where the two three-dimensional vortices are adjacent to one another, and if the data crossed the $x$-axis here it would mean that
the three-dimensional vortices removed all of the species from the blue volumes. This means that $C_c$ is approximately zero for the cases where $W \geq 24$ m. This trend levels off before crossing the $x$-axis and even begins to increase slightly.

In the $W = 8$ and $16$ m cases the blue control volumes in Figure 5-30 overlap, creating a flow field unlike the one assumed in this schematic (and shown in Figure 5-5 of two distinct three-dimensional vortices separated by a region with a flow field characterized by a primary vortex in the $x,z$-plane. The vortices are shown in for the $W = 8$ m case and the $W = 16$ m case in Figures 5-32(a) and 5-32(b), respectively. The flow fields in the cross canyons of the $W = 8$ and $16$ m cases are similar to the $W \geq 24$ m cases in that they are also characterized by two three-dimensional vortices, which are symmetric to one another across the $x,z$-plane in the center of the cross canyon. They also have mean flow entering the cross canyon via the upper part of the cross canyon-intersection interface and mean flow leaving the cross canyon in the lower part of the interface. While the vortices in the $W \geq 24$ m cases have aspect ratios of approximately unity ($L_{int}/L_{int}$), these vortices have aspect ratios of $W/(2L_{int})$. Assuming the structures in Figure 5-32 are equally effective at removing
Figure 5-31: \((C u_a) / (S H_s)\) vs. \(2 L_{int}/W\) at \(t = 60\) s, averaged over UCL volumes

species from the cross canyons, \(C_{c,total}\), may be approximated analytically as

\[
C_{c,total} = \frac{C_c (W L_{int}) + C_d \cdot 0}{W L_{int}} = C_c,
\]

meaning \(C_c\) is not negligible in these cases as in the \(W \geq 24\) m cases. Because the results show a slight positive slope in the \(W < 24\) m cases, the vortices with smaller aspect ratios in this context may be slightly less effective at laterally removing near ground species from the cross canyons than with an aspect ratio closer to unity.

The mean flow fields in the long canyons and intersections are not greatly affected by the changes in \(W\) for \(W \geq 24\) m, therefore the dimensionless concentrations in these are similar to the \(L = 80\) m case from Figure 5-17. The physical reasoning for these values was discussed in Section 5.1.1. The decreased lateral mixing in the cross canyons for the \(W < 24\) m cases is reflected in the decreased weighted average (by volume) of the dimensionless concentration in intersection and long canyon data,
relative to the other cases. The urban design implications of the results in Figure 5-29 will be discussed in Section 5.4.

### 5.2.2 Steady state results and relevant physics for variations in building width

The steady state dimensionless concentrations, bulk averaged over the UCL for the domain shown are displayed in Figure 5-27, are displayed against $W$ in Figure 5-33. As building width increases, the dimensionless concentration in the UCL decreases. Compared with the variation in dimensionless concentrations displayed in Figure 5-16, the dimensionless concentration varies less with changes in $W$ than with changes in $L$. This result and the applications to urban design will be discussed in more detail when both variables are varied in Sections 5.3 and 5.4.

The trend in Figure 5-33 may be explained through an understanding of the trends in the steady state dimensionless concentration data averaged over the UCL volumes, presented in Figure 5-34.

As in Section 5.1.2, it is helpful to compare the magnitudes of the long and cross canyon dimensionless concentrations with those of the infinitely long cases, shown in
Figure 5-33: \((C_{ss} u_a) / (S H_s)\) vs. \(W\) at steady state, averaged over the UCL

Figure 5-18. The long canyon concentrations in the cases simulated in Figure 5-34 are less than that of the infinite long canyon, and the cross canyons have greater concentrations than in the infinite cross canyon.

The differences between the dimensionless concentrations in the infinitely long cases and those shown in Figure 5-34 are because of intersections. The effect of the presence of intersections may be quantified at a neighborhood scale using Equation 5.7. Because the dimensionless concentration in the intersections is between that of the long canyons and the cross canyons, \((C_{ss} u_a) / (S H_s))_{\text{ideal}}\) is computed for Case 1

- Best case, where \((C_{ss} u_a) / (S H_s))_{\text{int,ideal}} = ((C_{ss} u_a) / (S H_s))_{\text{cross,ideal}}\) and Case 2
- Worst case, \((C_{ss} u_a) / (S H_s))_{\text{int,ideal}} = ((C_{ss} u_a) / (S H_s))_{\text{long,ideal}}\) These cases are plotted with the data from Figure 5-33 in Figure 5-35. The effect of the intersections is greater for small \(W\), which could be due to the presence of more intersections per unit plan area in these cases. These cases have inherently higher concentrations, however, due to the the fact that the dimensionless concentration of the long canyons

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Figure 5-34: \((C_{ss} u_a) / (S H_s)\) vs. \(W\) at steady state, averaged over UCL volumes is almost approximately 1.5 times that of the cross canyons for the data in Figure 5-34, and these small \(W\) cases have a large ratio of \(V_{long}\) to \(V_{cross}\) relative to other cases. The cases with large values of \(W\) have dimensionless concentrations that are slightly greater than the ideal cases in Figure 5-35, but the average dimensionless concentrations in the long canyons are less in the cases with intersections which leads to a more well-mixed neighborhood overall in comparison to the ideal case.

The street canyon scale trends in Figure 5-34 may be interpreted to some extent by considering the mean flow field in these domains. \(u_c/u_a\) is presented against \(W\) for the long canyons in Figure 5-36.

Using Equations 5.8, 5.9, 5.10 and 5.11 and the reasoning in Section 5.1.2, the decrease is dimensionless concentration relative to an infinitely long canyon due to increased vertical turbulent diffusion, \(\left( (C_{ss}/, u_a) / (S H_s) \right)_{long,T}\), is shown in Figure 5-37.
Recall the assumption made about the cross canyons in Section 5.1.2, that the discrepancies between the ideal cross canyon concentration and the cross canyon data in Figure 5-17 is only due to lateral mixing rather than changes in the mean vertical advection. This assumption is not valid for variations in $W$ because the mean flow in the cross canyons changes as $W$ varies. This is shown with three-dimensional streamlines, colored with dimensionless vertical velocity, $w/u_a$, for a variety of cases in Figure 5-38. The three-dimensional vortices affect the vertical mean flow in the cross canyon. The large flow structure adjacent and attached to the three-dimensional vortices shown in Figures 5-38(c)-(i) also affects the mean vertical flow in the cross canyon because it has noticeable components of $y$-velocity, unlike the infinitely long case. The symmetric flow structures in the center of the cross canyons in Figures 5-38(f)-(i), however, do not have a large component of $y$-velocity, and therefore are considered to behave approximately like the infinite cross canyon. When $W \leq 72$ m, the flow in entire cross canyon is significantly affected by the intersection. When
Figure 5-36: \( (u_c/\bar{u}_a)_{\text{long}} \) vs. \( W \), averaged over the long canyons

\( W \geq 80 \text{ m} \) only a portion of the flow in the cross canyon is significantly affected by the intersection, this portion is in the range of \( 1.4H \text{–} 2.0H \) on each side of the cross canyon, measured from the intersection-cross canyon interface. This is consistent with the findings of Soulhac et al. [2009] who found the range of influence of an intersection to be \( 1.4\text{–}2.2H \). The results for using the incorrect assumption of “only lateral mixing affects the concentration in the cross canyons,” \( ((C_{ss}/u_a)/(S H_s))_{\text{long},LT} \), are plotted with gray diamonds in Figure 5-39. The area between the black “x”s and the gray diamonds represents an upper limit of the possible contribution of lateral mixing towards species removal from the long canyons. Based on this, the estimated contribution of each time of species removal is shown in Figure 5-40.

The trends in Figure 5-34 are relatively flat in comparison to the neighborhood scale trend in Figure 5-33. This means that regardless of the cause of the enhanced species removal in the long canyons or the diminished species removal in the cross canyons relative to the infinite canyons, the trend in Figure 5-33 is largely due to the
ratio of $V_{\text{long}}$ to $V_{\text{cross}}$ in the neighborhood, i.e. long canyons are inherently worse at removing species that cross canyons, thus a neighborhood with more long canyons relative to cross canyons will have a larger average dimensionless concentration.

The steady state dimensionless concentration data at pedestrian height as it varies with $W$ is presented in Figure 5-41. As discussed in Section 5.1.2, the data averaged over the lowest 2 m of the domain will be larger in magnitude than the data averaged over the entire UCL due to the proximity of the constant volumetric source used in the CFD setup in this thesis. Similarly to when $L$ is varied, the cross canyon concentrations are $\sim 1.2$–$1.5$ times larger at pedestrian height than when averaged over the entire UCL, whereas the long canyon concentrations are about 2 times larger at pedestrian height. This is consistent with the previous argument that the larger increase in the long canyon data may be due to the near ground effect of the three-dimensional vortex, which advects species from the cross canyons to the long canyons.
Figure 5-38: Three-dimensional streamlines in cross canyons for cases: (a) $W = 8$ m, (b) $W = 24$ m, (c) $W = 56$ m, (d) $W = 64$ m, (e) $W = 72$ m, (f) $W = 80$ m, (g) $W = 104$ m, (h) $W = 136$ m, (i) $W = 160$ m
Figure 5-39: $\left(\frac{C_{ss} u_a}{S H_s}\right)_{\text{long}}$ vs. $W$ at steady state, turbulent effects and lateral effects.

Figure 5-40: $\left(\frac{C_{ss} u_a}{S H_s}\right)_{\text{long}}$ vs. $W$ at steady state, turbulent, lateral and mean effects.
The implications of the results in Figures 5-33, 5-34 and 5-41 for urban designers will be discussed in Section 5.4.

![Graph showing variations in intersection frequency](figure-5-41.png)

Figure 5-41: $(C_{ss} u_a) / (S H_s)$ vs. $W$ at steady state, averaged over pedestrian height UCL volumes, from $z = 0-2$ m

5.3 Variations in intersection frequency both parallel and perpendicular to the wind

The domain in Figure 5-42 was meshed, simulated and post-processed based on the approaches described in Sections 3.1 and 3.2. The cases simulated were $L = 16-144$ m in increments of 32 m, for each of the following: $W = 16, 48, 80, 112$ and 144 m. The dimensionless concentration is calculated for each case at neighborhood scale and at street canyon scale.
The transient concentration data at \( t = 60 \) s and the physics responsible for the trends in that data are discussed in Section 5.3.1. The steady state results and the flow phenomena responsible for them are presented in Section 5.3.2.

### 5.3.1 Transient results and relevant physics for variations in building length and building width

Based on Equation 5.6 and the discussion in Section 5.1.1, the dimensionless concentrations in the long canyons from the domain shown in Figure 5-42 are expected to vary linearly with \( 2 L_{\text{int}}^2 / (L W_{\text{int}}) \) at \( t = 60 \) s. These results are presented in Figure 5-43, and the trends are linear. Further, this data suggests that \( C_a \) and \( C_b \), displayed in Figure 5-11, which define the slope and \( y \)-intercept of the data in Equation 5.6 are nearly constant for all values of \( L \) and \( W \). Because these arguments are based on the flow physics, it makes sense that there is some deviation in the \( L = 16 \) m data, as discussed in Section 5.1.1. Additionally, one may feel confident interpolating this data as well as extrapolating this data for larger values of \( L \) and \( W \) because the phenomena causing this result is known (and explained in Section 5.1.1).

Based on Equation 5.16 and the discussion in Section 5.2.1, the dimensionless concentrations in the cross canyons should vary linearly with \( 2 L_{\text{int}} / W \) at \( t = 60 \) s.
These linear trends are presented in Figure 5-44. This data also suggests that $C_c$ and $C_d$ from Figure 5-30, which define the slope and the y-intercept of the lines are approximately constant for all $L$ and $W$ that were simulated. Based on the discussion of the flow physics in Sections 5.1.1 and 5.2.1, it makes sense that there are some discrepancies in the $L=16$ m and $W=16$ m data, respectively. This data may be interpolated with confidence, and may be extrapolated to larger values of $L$ and $W$ because the flow phenomena responsible for these trends are understood and were explained in Section 5.2.1.

The implications of these results as they pertain to urban design applications will be discussed in Section 5.4.
5.3.2 Steady state results and relevant physics for variations in building length and building width

The steady state dimensionless concentration which is bulk averaged over the UCL, \((C_{ss} u_a) / (S H_s)\), is displayed for variations in building length and building width in Figure 5-45. In general, the gradient of this data is steeper along the \(L\)-axis than along the \(W\)-axis. This is consistent with a comparison of the neighborhood scale data from \(L = 80\) m in Figure 5-16 and the data from \(W = 80\) m in Figure 5-33. Increasing \(W\) simply shifts the proportion of the UCL volume which is made up of cross canyons relative to long canyons. This results in a decrease in the average concentration at a neighborhood scale because cross canyons remove more pollutants than long canyons at steady state, regardless of their width. Varying \(L\) also shifts the proportion of the UCL volume which is made up of cross canyons relative to long canyons, however it also leads to significant changes in velocity field in the long canyons, which changes
Figure 5-45: Contours of \( \frac{(C_{ss} u_a)}{(S H_s)} \) for \( W \) [m] vs. \( L \) [m] at steady state, averaged over the UCL.

The magnitude of the species flux to the UCL due to vertical turbulent diffusion (the flux is increases relative to the infinitely long case). This change is responsible for removing more species at smaller values of \( L \) as discussed in Section 5.1.2 and shown in Figure 5-25. This is responsible for the larger gradient for variations in \( L \) than for variations in \( W \), shown in Figure 5-45.

\( \frac{(C_{ss} u_a)}{(S H_s)} \) is shown averaged over the pedestrian height in Figure 5-46 for variations in \( L \) and \( W \). The trends are similar to those found when the concentration was averaged over the UCL, however the magnitude of the concentrations is greater than those in Figure 5-45. As previously discussed, this is due to the proximity of this data to the near ground constant volumetric source.

The implications of these results as they relate to urban design will be discussed in Section 5.4.
Figure 5-46: Contours of \((C_{ss} u_a)/(S H_s)\) for \(W \text{ [m]}\) vs. \(L \text{ [m]}\) at steady state, averaged over pedestrian height within the UCL, from \(z = 0-2 \text{ m}\)

### 5.4 Implications

The results in Sections 5.1–5.3 could be used by an urban designer to inform decisions about building or city block layout at a neighborhood scale. As evidenced by Figures 5-45 and 5-46, a repetitive gridded neighborhood removes more scalars when the longer side of the building is oriented perpendicular to the wind \((W)\), and the shorter side of the building is oriented parallel to the wind \((L)\). If air quality or urban heating is a concern in a particular city, the best solution for a gridded neighborhood would be to have “slab” architecture perpendicular to the dominant wind direction, i.e. wide buildings that are short in length along the direction of the wind. Buildings of the same dimensions, rotated ninety degrees, are the worst scenario when using steady state dimensionless concentration in a domain with a constant near ground source as the metric for mixing or “breathability.” Based on Figures 5-45 and 5-46,
variations in $W$ have less of an effect on the neighborhood-averaged concentration than variations in $L$. This is due to the reductions in turbulent exchange between the long canyons and the UBL as these street canyons increase in length.

Urban designers have considerations other than air quality when designing the layout of a new neighborhood. It is not always possible to create rectangular buildings with $W \gg L$ due to restrictions in the land area of a planned neighborhood, for example, because rectangular buildings require more land area of streets between them than square buildings assuming $L_{int} = W_{int} = \text{constant}$. Another factor may be a minimum requirement for built volume, which is directly related to population capacity, in the new neighborhood. To enable an urban designer to quantify the impact of changing the shape of a building on dimensionless concentration the ratio $\beta$ is introduced:

$$\beta = \frac{V_{\text{buildings}}}{A_{\text{plot}}}, \quad (5.17)$$

where $A_{\text{plot}}$ is the land area available for the new gridded neighborhood and $V_{\text{buildings}}$ is the built volume that is necessary in that land area to perform all of the necessary functions of the neighborhood (residential, commercial, etc.). For a repetitive, orthogonally gridded neighborhood of constant height, Equation 5.17 may be rewritten in terms of the parameters in Figure 5-42 as:

$$\beta = \frac{LWH}{(L+L_{int})(W+W_{int})}. \quad (5.18)$$

In Figure 5-47, lines of constant $\beta$ were plotted over the data from Figure 5-45 for the range of $\beta = 10 - 17$ m. The contours are also plotted over the pedestrian height data from Figure 5-46 in Figure 5-48. Figures 5-47 and 5-48 are graphic tools that could be useful to urban designers. For a fixed value of $\beta$, it is easy to weigh the trade-offs in neighborhood-scale vertical mixing for small or large changes in building dimensions.

Consider a scenario where $\beta = 13$ m is the minimum built volume to land area ratio required for a particular development. If the neighborhood in design is in the lower right-hand portion of the graph, a designer may induce a measurable reduc-
tion in neighborhood-averaged steady state concentration by changing the building parameters to move the design further left on the $\beta = 13$ m contour. One may also see that a similar reduction in concentration can be achieved by simply increasing the width of buildings, leading to an increase in $\beta$ and more built volume than the minimum required. This could be used for an additional public space above and beyond those planned, which could improve the community. If the designed neighborhood is set to have square buildings in plan, however, the effect of changing the building parameters to reduce the concentration is somewhat diminished, and the trade-off of changing the design to improve neighborhood scale mixing may not be worth it when other design parameters are considered.

At a street canyon scale, cross canyons have lower steady state dimensionless concentrations than long canyons in all cases, and intersection concentrations are between the long canyon data and the cross canyon data for a particular case at
Figure 5-48: Contours of \((C_{ss} u_a)/(S H_s)\) for \(W\) [m] vs. \(L\) [m] at steady state, averaged over pedestrian height within the UCL, from \(z = 0\) to \(2\) m with contours of constant \(\beta\).

steady state. The exact results averaged over the UCL and averaged over pedestrian height are presented in Appendices B.1 and B.2. These street canyon results may influence design decisions, e.g. restaurants with outdoor seating or large windows at street level would have better air quality if situated in a cross canyon than in a long canyon. Long canyons may be more suited to façades with no windows or entrances or to windows for egress spaces, such as stairwells, which are unlikely to be used for natural ventilation of the rest of the building.

The data at \(t = 60\) s, presented in Sections 5.1.1, 5.2.1 and 5.3.1 (and summarized in Figures 5-43 and 5-44) is useful for developing an understanding of the flow phenomena responsible for laterally advecting passive scalars, which is necessary for meeting the second goal of this thesis. It could also be useful in an urban design context as well. Though a near-ground constant volumetric source was used to assess
vertical mixing potential of neighborhoods and street canyons in this work, heat and pollutant sources in real cities are more varied, both in time and space. For example, a single car idling at a traffic light or stop sign may act more like a transient source (i.e. a constant source present only for the seconds that the car is stopped) of fixed size in a cross canyon near the interface of the intersection. The immediate effect of this would be a flux of pollutants from the edge of the cross canyon to the intersection and into the long canyon. This would increase the concentration in the long canyon slightly for some length of time, in addition to concentration from the more evenly distributed sources such as anthropogenic heat from humans and automobiles in motion. This effect would be exacerbated if this stop light with one car were instead a frequently used bus stop. Time scales associated with the lateral and vertical development of species fields will be discussed in Chapter 6.

The results in this chapter quantified the influence of varying the intersection frequency along both axes in an orthogonally gridded city aligned with the wind, thereby meeting the first goal of this thesis for these parameters. The results were explained physically and were summarized in graphics that would be useful to urban designers who are weighing the effects of modifying building layout on the mixing potential of the neighborhood and on the air quality in specific street canyon volumes. This meets the second and third goals of this thesis.
Chapter 6

Street canyon aspect ratio

This chapter focuses on the effect of varying building height in an orthogonally gridded neighborhood with buildings of uniform height, oriented parallel to the wind. This parameter affects the steady state dimensionless concentration, and was presented non-dimensionally as the street canyon aspect ratio in Equation 4.18, restated here:

\[
\frac{C_{ss} u_a}{S H_s} = g_9 \left( C_f, \frac{L}{L_{int}}, \frac{W}{L_{int}}, \frac{H}{L_{int}}, \frac{W_{int}}{L_{int}} \right).
\]

The effect of varying the aspect ratio of cross canyons on the mean flow field within the UCL and pollutant transport out of the UCL is a well studied problem. These effects are reviewed and summarized by Li et al. [2006] for a two-dimensional cross canyon for aspect ratios ranging from \(H/L_{int} = 0.5\)–3.5. Two-dimensional cross canyon studies for larger aspect ratios (up to \(H/L_{int} = 5\)) are studied by Li et al. [2008b], and the \(H/L_{int} = 10\) case is studied by Li et al. [2009]. These studies found that increasing street canyon aspect ratio led to an increasing number of recirculations in the flow field as well as increases in pollutant concentrations in these cross canyons. Li et al. [2008b] calculated that for a near ground line source of pollutants oriented along the axis of the cross canyon and centered along the width of the canyon, the average non-dimensional pollutant concentration in the \(H/L_{int} = 5\) case was more
than two orders of magnitude greater than that of the $H/L_{int} = 2$ case. These will be compared to the calculations of this thesis in Section 6.4.2.

There has been less work on the effect of varying the aspect ratio of long canyons. Soulhac et al. [2008] develop an analytical model to predict the flow field in an infinitely long street canyon aligned with the wind for any aspect ratio based on the assumption that each point in the street canyon flow field is only affected by the nearest wall as discussed in Section 2.4. They quantified the decrease in the mean flow field found with increasing aspect ratio. Hang et al. [2010a] calculates the air change rates in long street canyons aligned with the wind for $H/W_{int} = 2-4$. They conclude that in the fully developed region, long canyons with larger aspect ratios have smaller air change rates due to less turbulent fluctuation in the flow field.

As discussed in Chapter 5, intersections influence the concentrations at both a neighborhood and a street canyon scale due to changes in the mean, lateral and turbulent mixing of scalars among the various street canyon volumes in comparison to infinitely long canyons which are affected only by the UBL. A brief review of studies considering gridded neighborhoods with intersections is presented at the beginning of Chapter 5. The effect of varying building height, or non-dimensionally, the street canyon aspect ratios, on mixing between the UCL and the UBL in an orthogonally gridded neighborhood is studied in this thesis using a domain which varies only $H/L_{int}$ from the list of geometric parameters in Equation 4.18 and keeps all other dimensionless parameters constant.

The simulation domains and the selection of time-steps used to post-process the concentration data for neighborhoods with different street canyon aspect ratios are discussed in Section 6.1. In Section 6.2, the transient concentration data is presented and the physics responsible for the trends in this data are discussed. The steady state concentration data and the relevant physics are explained in Section 6.3. The implications of the selected domain and the urban design applications based on the transient and steady state results are discussed in Section 6.4.
6.1 Post-processing data for neighborhoods with different average street canyon aspect ratios

The domain shown in Figure 6-1 was meshed and simulated as discussed in Section 3.1 and post processed as discussed in Section 3.2 for each of the following cases: $H = 20, 30, 40, 50, 60, 70$ and $80$ m. The dimensionless concentrations are computed for each of these cases at both a neighborhood scale and at a street canyon scale.

(a) $L_{int} = 10$ m $L = 80$ m

(b) $W = 80$ m

Figure 6-1: Simulation domain for cases where $H$ is varied

Because the time constants will vary with aspect ratio, the dimensionless concentration data is simulated for each case at various predetermined time steps. The following times were saved for each case until a steady dimensionless concentration is reached: 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 70, 80, 90, 100, 110, 120, 140, 160, 180, 200, 220, 240, 280, 320, 360, 400, 440, 480, 560, 640, 720, 800, 880, 960, 1120, 1280, 1440, 1600, 1760, 1920, 2240, 2560, 2880, 3200, 3520, 3840, 4480, 5120, 5760, 6400, 7040, 7860, 8320, 8960, 9600, 10240 and 10880 seconds.

The unprocessed dimensionless concentration data is shown in Figure 6-2. This is the same step in the post processing technique as the green dashed line shown in Figure 3-6. As expected, there is a linearly increasing component of this data which is related to the form of Equation 3.26. After subtracting this ramp component from
Figure 6-2: $(C u_a)/(S H_s)$ vs. Time [s] for the unprocessed simulation data at various values of $H/L_{int}$

the raw data and adjusting the data by $N$, defined in Equation 3.37, for reasons discussed in Section 3.2, the dimensionless concentration data reaches a steady state as shown for all values of $H/L_{int}$ in Figure 6-3. This is equivalent to the black circles shown in Figure 3-6.

The data shown in Figure 6-3 was fit to the form of Equation 3.38 then nondimensionalized as discussed in Section 4.2. In these cases the concentration at $t = 0$ is zero, therefore Equation 3.38 may be simplified to a form with two unknowns as:

$$C(t) = C_{ss} \left( 1 - e^{-t/\tau} \right),$$

where $C(t)$ [kg/m$^3$] is the concentration averaged over the UCL at a particular time, $C_{ss}$ [kg/m$^3$] is the steady state concentration averaged over the UCL and $\tau$ [s] is the time constant of this function. The constants in Equation 6.1 were found using the MATLAB nonlinear least-squares regression tool, nlinfit. Each of the data points
shown in Figure 6-3 was prescribed an equal weight for a given $H/L_{int}$. Table 6.1 shows the resulting constants, where $C_{ss}$ has been non-dimensionalized as discussed in Section 4.2.

Curves based on the data in Table 6.1 are shown plotted over the data from Figure 6-3 in Figure 6-4. This is Step 3 of post-processing, as presented at the end of Section 3.2. The dimensionless concentrations in Table 6.1 do not reflect the idealization necessary due to the finite geometry of the domain (Step 4 in Section 3.2). These curves tend to slightly over predict the steady state concentration as well as the time constant, and this effect is more pronounced as $H/L_{int}$ increases. This is due to the fact that the time steps used in the fitting are more heavily concentrated at small values, therefore a nonlinear fit with equal weighting on each of these points will fit the rise of the first order step response more accurately than it will fit the final value. For this work, however, accurately predicting the final value is more important than predicting the trend in the data at small times.
Table 6.1: $\left(\frac{C_{ss} u_a}{S H_s}\right)$ and $\tau$ for various $H/L_{int}$ fitted using all of the post-processed simulation data

<table>
<thead>
<tr>
<th>$\frac{H}{L_{int}}$</th>
<th>$\frac{(C_{ss} u_a)}{(S H_s)}$</th>
<th>$\tau$ [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>126.7</td>
<td>228.2</td>
</tr>
<tr>
<td>3</td>
<td>160.1</td>
<td>405.7</td>
</tr>
<tr>
<td>4</td>
<td>152.7</td>
<td>512.9</td>
</tr>
<tr>
<td>5</td>
<td>160.7</td>
<td>673.4</td>
</tr>
<tr>
<td>6</td>
<td>169.3</td>
<td>852.3</td>
</tr>
<tr>
<td>7</td>
<td>188.5</td>
<td>1098</td>
</tr>
<tr>
<td>8</td>
<td>221.4</td>
<td>1429</td>
</tr>
</tbody>
</table>

It is not feasible to save, extract data from, and post-process 10 or more time step simulations to calculate the steady state concentration for a single case. Saving a single simulation at $t \to \infty$ to predict the final value is not a good solution because it has no information about the rise, and the time constant may be relevant for some applications. Additionally, a single value at $t \to \infty$ may lead to simulations running for longer times than necessary to ensure that the concentration at $t$ is within some tolerance of the steady state value.

The approach used in this thesis is based on knowledge of the form of $C(t)$, the time constant and the flow field with a goal of predicting the time constants and steady state concentrations of the data in Figure 6-3 accurately. Secondary goals include using as few time steps as possible and time steps with the smallest possible values to reduce the number of simulations and time necessary to run the simulations.

For this work, time steps are saved at $t = 0$, $t \approx \tau$ and $t \approx 4\tau$. Fitting these values to the function in Equation 6.1 results in accurate predictions of the steady state concentration and the time constant. Of course using these time steps assumes a priori knowledge of $\tau$. If $\tau$ is known for a particular geometry, it may be extrapolated for different values of $u_a$ following the arguments in Section 4.3. For neighborhoods of different geometries with buildings of the same height, one may assume that $\tau$ will be most affected by changing the aspect ratios of the street canyons, $H/L_{int}$ and $H/W_{int}$. This is because the removal of species from the UCL to the UBL in the neighborhoods with buildings of a constant height is necessarily vertical due
Figure 6-4: $(C_{\text{u}_a})/(S_{\text{H}_a})$ vs. Time [s] for post-processed simulation data at various values of $H/L_{\text{int}}$ fitted using all data with equal weighting to the periodic and symmetry boundary conditions. Therefore, the results shown in Table 6.1 may be used to predict the time steps that should be used to fit the concentration data in all repetitive, gridded neighborhoods of fixed building height with $H/L_{\text{int}} = H/W_{\text{int}}$ in the range of $H/L_{\text{int}} = 2-8$, with similar values of $W/L_{\text{int}}$ and $L/L_{\text{int}}$. (Note: time constants for infinite canyons, presented in Figure 6-27, provide a more conservative estimate and should be used to determine simulation time steps for $H/L_{\text{int}}$ simulations with $W/L_{\text{int}}$ and $L/L_{\text{int}}$ values that are not similar to the work in this chapter.) Supplementary time steps are also saved at $t \approx \tau/4$ and $t \approx \tau/2$, and are used with reduced weighting in the non-linear fitting procedure. This mitigates the rise of first order step response being well-fit at the expense of the steady state value as in Figure 6-4, yet it ensures that time constant is well-predicted even if the a priori estimate of $\tau$ is too large by guiding the shape of the first order step response at small times. The weighting for each of these supplementary time steps was set to five percent of the other time steps. The time constants presented in
Table 6.1 are rounded to the nearest simulation time, and these approximate values are used to calculate the necessary time steps for fitting the data using fewer time steps with this approach. These time steps are presented in Table 6.2.

The fitted curves based on the weighted non-linear fit approach and the time steps in Table 6.2 are overlaid on the curves and data from Figure 6-4 in Figure 6-5. The new fits are shown with red dashed lines. These lines appear to match the steady state values of the data better than the fits based on all of the simulated time steps.

The differences between the two fits are compared in Figure 6-6(a) by plotting the steady state dimensionless concentration found with the weighted approach against the steady state dimensionless concentration found when using all of the data. Figure 6-6(b) shows the same comparison of fits for the time constants. The differences between these two fitting techniques are most noticeable in the time constant data for the larger values of $H/L_{int}$ which is likely due to the increasing number of time steps originally used for fitting in the range of $t < \tau$ as $H/L_{int}$ increases. As previously discussed this promotes a more accurate fit for the rise part of the first order step response and a less accurate fit near the time constant and the final value. In general, the deviations shown in Figure 6-6 due to fitting technique are negligible for the dimensionless steady state concentration relative to the scale of the trends in dimensionless concentration due to varying geometric parameters in Chapter 5 (and the rest of this thesis). To this end, this fitting technique based on an a priori estimate of the time constant based on the wind speed as discussed in Section 4.3 and

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<tr>
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<td>360</td>
<td>720</td>
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<td>5760</td>
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</table>
Figure 6-5: \( \frac{C_{u_a}}{SH_s} \) vs. Time [s] for post-processed simulation data at various values of \( H/L_{int} \) fitted using all data and with equal weighting and using a weighted fit.

The aspect ratio of the street canyons is used throughout this research, and should be used when simulating cases not considered in this work. Using this approach, it is better to over estimate \( \tau \) than to underestimate it a priori if calculating the steady state concentration accurately is the primary goal to ensure that at least one time step with full weight is near the steady state value. Therefore, \( \tau = 240 \text{ s} \) was used throughout Chapter 5 rather than \( \tau = 220 \text{ s} \) to fit the intersection frequency data for \( H/L_{int} = H/W_{int} = 2 \). A conservative estimate of \( \tau \) should be drawn from the infinite canyon time constants shown in Figure 6-27. If \( H/L_{int} \neq H/W_{int} \), a case discussed in Chapter 9, using the larger aspect ratio to estimate \( \tau \) is the prudent choice to ensure accurate prediction of the steady state concentrations. This choice, however, will lead to longer simulation times.
6.2 Transient results and relevant physics for variations in street canyon aspect ratio

In Sections 5.1.1 and 5.2.1 data at $t = 60$ s is studied to examine the lateral mixing among the UCL volumes. The mostly horizontal trends in Figures 5-2 and 5-28 suggest that at $t = 60$ s the domains being studied are at approximately the same stage in the development of the species field, meaning these domains have approximately the same time constant. This further confirms the argument made in Section 6.1 that the time constant will be a function of a street canyon aspect ratio rather than one of the lateral dimensionless length scales. To make a similar transient comparison of studying the effect of street canyon aspect ratio to those in Chapter 5, one must choose the time studied based on a time constant scale rather than a time scale. This is accomplished by considering the mass of CO in the street canyon at a given fraction of $\tau$, normalized by the total mass of CO released after that amount of time, hereafter referred to as $\Phi$. This is expressed in equation form as:

$$\Phi = \frac{C V_0}{m (t = \gamma \tau)},$$

(6.2)
where \( \gamma \) is the fraction of the time constant and \( m(t = \gamma \tau) \) is
\[
m(t = \gamma \tau) = \int_{t=0}^{t=\gamma \tau} \int_{V_s} S \, dV_s \, dt.
\]
\( \Phi \) is plotted for \( \gamma = 0.25, 0.5, 1 \) and 4 in Figure 6-7. These are the values used for fitting the data in Section 6.1. Figure 6-7 shows that these cases develop similarly in the sense of vertical removal of scalars as a function of \( \tau \), yet the magnitude of the dimensionless concentrations are not similar due to the magnitude of \( \tau \) which is a function of the street canyon aspect ratios. At \( \gamma = 0.25 \) more than 95% of the species released into the neighborhood remains in the UCL. Though there has not been much vertical mixing from the UCL to the UBL at this time, there may still be lateral mixing between the UCL volumes defined in Figure 3-7. These street canyon concentration results are presented normalized by the bulk averaged neighborhood-scale concentration data, \( C_{\text{neighborhood}} \) for each aspect ratio in Figure 6-8. These results may be understood by considering the surface streamlines projected onto \( x, y \)-planes.
Figure 6-8: Average street canyon concentration, normalized by average concentration in the UCL vs. $H/L_{int}$ at $\tau/4$

for each aspect ratio as Figure 5-9 was used for $H/L_{int} = 2$ in Chapter 5. Views at the same nine values of $z/H$ are shown for $H/L_{int} = 3, 4, 5, 6, 7$ and $8$ in Figures 6-9, 6-10, 6-11, 6-12, 6-13 and 6-14, respectively. Only the $y \leq 0$ sides of the views are shown because the results are symmetric about the $y = 0$ plane.

Figure 6-9: Plan views of the streamlines for the $H/L_{int} = 3$ case at various heights

While the three-dimensional vortex is not observed in the same form as seen in Figure 5-9 for the $H/L_{int} = 2$ case, there is still mean flow from the cross canyons
Figure 6-10: Plan views of the streamlines for the $H/L_{int} = 4$ case at various heights.

Figure 6-11: Plan views of the streamlines for the $H/L_{int} = 5$ case at various heights.

Figure 6-12: Plan views of the streamlines for the $H/L_{int} = 6$ case at various heights.
Figure 6-13: Plan views of the streamlines for the $H/L_{int} = 7$ case at various heights

Figure 6-14: Plan views of the streamlines for the $H/L_{int} = 8$ case at various heights
into the long canyons at smaller values of $z/H$ and mean flow from the long canyons into the cross canyons at larger values of $z/H$ for these larger street canyon aspect ratios. As in Chapter 5, this results in the long canyons having higher concentrations than the cross canyons at $\gamma = 0.25$ due to the near-ground location of the volume source from which the species is released. The transition from positive to negative $v/u_a$ at the cross canyon and intersection interface occurs at increasingly large $z/H$ as $H/L_{int}$ increases. This transition height, $z_t/H$ is plotted in Figure 6-15, where the $y$-axis represents the approximate height at which a transition such as the one shown at $z/H = 0.3$ in Figure 5-9 occurs. As $z_t/H$ increases, the fraction of the cross canyon-intersection interface contributing to the transfer of species from the cross canyon to the long canyon increases. This phenomenon is discussed in depth in Section 5.1.1. At small times, when the species field is still developing vertically, the species will be concentrated in the UCL, with greater concentrations at smaller values of $z/H$. Based on this, one may expect that increases in $z_t/H$ will lead to an increase in the amount of species transferred from the cross canyon to the long canyon at small times. This explains the trends in the long canyon and cross canyon data for $H/L_{int} = 2–5$ in Figure 6-8.

Based on the trend in Figure 6-15, one may expect the non-dimensional concentration in long canyons and cross canyons to level out for $H/L_{int} > 5$. Instead the long canyon data increases to $H/L_{int} = 6$, and then decreases for $H/L_{int} = 7$ and 8. This may be explained by the decrease in normalized $y$-velocity, $v/u_a$ as aspect ratio increases, shown in Figures 6-9–6-14. This is due to increased rough walls per unit plan area in these domains, resulting in increased drag force applied to the fluid which results in a reduction in wind speeds in the UCL. This is further evidenced by the decrease in average $(u_c/u_a)_{long}$ in the long canyons as $H/L_{int}$ increases, shown in Figure 6-16. This will lead to a reduction in the velocity used in the calculation of the mean flux of pollutants into and out of the cross canyon along the cross canyon-intersection interface. This reduction in velocity will contribute to a smaller average flux across the interface at a given dimensionless height. This may be responsible for the reduc-
Figure 6-15: Height of transition from positive to negative $v/u_a$ at cross canyon-intersection interface, $z_t/H$ vs. $H/L_{int}$

In addition to these two competing effects (increasing $z_t/H$ and decreasing $v/u_a$ with increasing $H/L_{int}$), there is another feature of the flow fields that may contribute to the shape of the normalized long canyon data in Figure 6-8. Consider the $x,z$-views of the three-dimensional streamlines for the $H/L_{int} = 3-8$ cases in Figure 6-17(a)-(f), respectively. In each of these cases the streamlines enter the cross canyons over the approximate range of $z/H$ of $z_t/H < z/H < 1$, where $z_t/H$ is the approximate value shown in Figure 6-15. These streamlines entering the cross canyons pass through a wide range of $z/H$ in the preceding long canyons. This means scalars near the ground in the long canyon are vertically advected within the long canyon, then laterally advected into the upper portion of the cross canyon. This is in contrast to the $H/L_{int} = 2$ case, shown in Figure 5-10(a). This will result in a decrease in long canyon concentration, and this effect will be more prevalent for those cases with
larger values of \( (u_c/u_a)_{long} \) (meaning smaller values of \( H/L_{int} \)) as these cases will more quickly advect the species along the long canyon in the \( x \)-direction.

The cross canyon and long canyon concentrations are almost perfectly symmetric about a value of unity in normalized concentration in Figure 6-8. They would be perfectly symmetric if the intersection normalized concentrations were unity. The intersection concentrations are particularly low in the \( H/L_{int} = 3 \) case. Some of the streamlines leaving the near ground portion of the cross canyon and entering the intersection in Figure 6-17(a) are in the reverse flow direction because of the sudden expansion effect discussed in Chapter 5. The other streamlines are more vertical after leaving the cross canyon, then follow the mean flow direction in the long canyon. In the other cases, shown in Figure 6-17(b)-(f), however, the streamlines leaving the cross canyons are vertical over a greater proportion of the height of the intersection, which will lead to higher concentrations in that volume than in the \( H/L_{int} = 3 \) case.
This vertical motion is further evidenced by $y,z$-views of the flow structures in the cross canyons, shown for $H/L_{int} = 3 - 8$ in Figures 6-18(a)–(f), respectively.

The structure shown in Figure 6-18(a) is similar to that shown for the cross canyons for $H/L_{int} = 2$ in Figure 5-38. The three-dimensional vortices for the cases with larger aspect ratios have different flow structures. In these cases the $x$-vorticity is more dominant than the $z$-vorticity, especially for $H/L_{int} \geq 6$. This is also apparent in the lack of recirculation zones in the cross canyons in Figures 6-10–6-14 relative to Figures 5-9 and 6-9. To understand this, these structures are shown in three-dimensional views in Figure 6-19. The shape of the structure in Figure 6-19(a) is similar to the $H/L_{int} = 2$ case and is discussed in Chapter 5. The enhanced recirculation in the $y,z$-plane in the other cases is due to the streamlines moving in the $-y$-direction below the structure shown in Figures 6-18(b)–(e). This drives the
rotation of that structure and subsequently drives the vertical flow of the fluid in the intersection in these cases. Similar flow fields were seen in the $W = 24$ m case for $H/L_{int} = 2$, shown in Figure 5-38(b). As discussed in Section 5.2.2, this case has a different flow structure than the cases with larger values of $W$ because the effect of the intersection extends $1.4H - 2.0H$ into the cross canyons. The implications of the choice of these relatively small values of $L/H$ and $W/H$ will be discussed in Section 6.4.1. Methods to extend this work to other values of $L/H$ and $W/H$ as well as the implication of these results with respect to urban design applications will be discussed in Section 6.4.2.

Figure 6-18: Three-dimensional streamlines in the cross canyons shown in a $y,z$-plane: (a) $H/L_{int} = 3$, (b) $H/L_{int} = 4$, (c) $H/L_{int} = 5$, (d) $H/L_{int} = 6$, (e) $H/L_{int} = 7$, (f) $H/L_{int} = 8$
Figure 6-19: Three-dimensional streamlines near an intersection: (a) $H/L_{int} = 3$, (b) $H/L_{int} = 4$, (c) $H/L_{int} = 5$, (d) $H/L_{int} = 6$, (e) $H/L_{int} = 7$, (f) $H/L_{int} = 8$

6.3 Steady state results and relevant physics for variations in street canyon aspect ratio

The steady state dimensionless concentration bulk averaged over the entire UCL, $(C_{ss} u_a) / (S H_s)$, is displayed in Figure 6-20 for the domain in Figure 6-1 over the range of $H/L_{int}$ considered. These results were calculated using the technique discussed in Section 6.1 and the time steps displayed in Table 6.2 (and $t = 0$ s). In general, as street canyon aspect ratio increases, the dimensionless concentration in the UCL increases. The results for $H/L_{int} = 2$ and 3 are not part of the smooth trend seen in the $H/L_{int} = 4 - 8$ results. This is because the higher aspect ratio
results have fundamentally different flow fields due to the intersection affecting the entire cross canyon flow field, as discussed in Section 6.2. These higher aspect ratio results are comparable to studying only the lower left hand portion of Figure 5-45 in the sense that the length and width of the buildings in these neighborhoods are only 1-2 times larger than the building height, and thus all UCL volumes are heavily influenced by the presence of intersections as discussed for the smaller values of $L$ and $W$ in Chapter 5.

Figure 6-20: $\frac{(C_{ss} u_a)}{(S H_s)}$ vs. $H/L_{int}$ at steady state, averaged over the UCL volumes.

The trend in Figure 6-20 may be further explained with an understanding of the trends in the steady state concentration data in the UCL volumes, shown in Figure 6-21. In general the long canyons have larger concentrations than the cross canyons for a particular value of $H/L_{int}$ for reasons discussed in Chapter 5 and Section 6.2. The pedestrian height results at a neighborhood scale and for the UCL volumes for $H/L_{int}=2-8$ are shown in Appendix B.3 in Figures B-7 and B-8, respectively.
The meshes required to simulate the ranges of $L/H$ and $W/H$ studied in Chapter 5 are prohibitively computationally intensive using the techniques described in Section 3.1 for larger street canyon aspect ratios. Because the effect of the intersections largely dominate the results for higher values of $H/L_{int}$ in Figures 6-20 and 6-21, it is useful to consider the effect of the street canyon aspect ratio without intersections. To this end, infinite long canyons and cross canyons were simulated for each aspect ratio using a similar setup and domain to that shown in Figure 5-18 and discussed in Section 5.1.2. These results are presented in Figure 6-22. Based on the arguments made in Section 5.1.2, it is reasonable to assume that the steady state concentrations in long canyons gradually approach the steady state concentration in an infinitely long canyon of the same aspect ratio. The cross canyons in Chapter 5 have consistently higher concentrations than the infinitely long cross canyon of the same aspect ratio as shown in Figure B-2. It stands to reason that a long enough cross canyon, sufficiently far from upwind and downwind cross canyons would eventually behave as an infinite cross canyons.
canyon with similar steady state concentrations, however this affect must occur at larger values of $W/H$ and $L/H$ than those considered in Chapter 5. The implications of these results are discussed as they pertain to urban design are discussed in Section 6.4.

![Figure 6-22: $(C_{ss} u_a) / (S H_s)$ vs. $H/L_{int}$ and $H/W_{int}$ at steady state for idealized, long canyons and cross canyons](image)

Figure 6-22: $(C_{ss} u_a) / (S H_s)$ vs. $H/L_{int}$ and $H/W_{int}$ at steady state for idealized, long canyons and cross canyons

### 6.4 Implications

The implications of the domain selection for this chapter are reiterated in Section 6.4.1 and the implications of the results in the context of urban design are presented in Section 6.4.2.
6.4.1 Domain selection implications

The results in Section 5.2.2 suggest that the intersections influence the flow fields in the cross canyons over a distance of $1.4 - 2.0H$ from the intersection-cross canyon interface. This is similar to the results found by Soulhac et al. [2009]; they found the range of influence of an intersection to be $1.4-2.2H$. The discrepancy is discussed in Section 5.2.2. Assuming this finding is true for these cases with larger values of $H/L_{int}$, the flow structures shown in Figures 6-18(b)-(e) may well become more like Figure 6-18(a) if the cross canyons were longer. This could result in cross canyons with non-dimensional steady state concentrations of the same orders of magnitude as the infinite results shown in Figure 6-22. The domain selections in this chapter may be more realistic for an urban area than infinitely long street canyons with large aspect ratios, however these selections cause the discussion in Sections 6.2 and 6.3 to be based on dimensional reasoning, inference based on the flow physics found in Chapter 5 and general fluid mechanical intuition. This is in contrast to the discussion in Chapter 5, which was heavily supported by CFD results. Though this is not ideal, it was necessary due to computational limitations associated with studying gridded neighborhoods with much longer street canyons.

6.4.2 Urban design implications

The results in Sections 6.2 and 6.3 could be used by an urban designer or policy maker to understand the implications of increasing the street canyon aspect ratio, $H/L_{int}$ (where $W_{int}/L_{int} = 1$), in an orthogonally gridded urban area of buildings with constant height aligned with the wind. Figure 6-20 shows that increasing the street canyon aspect ratios leads to an increase in the scalars retained in the UCL from a near ground release. If removing heat or pollutants from near ground sources is a concern in a similar neighborhood, Figure 6-20 suggests that gridded neighborhoods with smaller aspect ratios are better than those with larger aspect ratios for the same building layout in plan view.
As mentioned in Section 6.3, to understand the implications of a range of cases such as those studied in Chapter 5 ($L/H = 0.8-8.0$ and $W/H = 0.8-8.0$) it is worth considering the infinite canyon results. This is because the gridded neighborhood domains selected in this chapter only capture a point equivalent to the bottom left corner of the surface plot shown in Figure 5-45. The infinite canyon results for $H/L_{int} = 2$ were combined using Equation 5.7 to compare these infinite results to gridded neighborhoods over a range of $L$ in Figure 5-19 and over a range of $W$ in Figure 5-35. The infinite results were the same order of magnitude as the actual results, and the slopes of the infinite data approach the slope of the actual results as $L$ and $W$ increase. It is therefore interesting to consider the infinite results as a means of predicting the approximate magnitude of the non-dimensional concentration as well as the trend in that data due to varying values of $L/H$ and $W/H$. Because the slope of the infinite canyon prediction appears to match that of the actual results at $L/H > 4$ in Figure 5-19, this value is chosen as a starting point for using this technique at higher aspect ratios. $W/H = 4$ is selected as a starting point for symmetry, however it is likely that this technique will become increasingly more predictive at larger $W/H$ values. This ensures we are outside or at the edge of the range where the cross canyon flow fields are directly affected by the intersection as discussed in Section 6.4.1. The cases are studied through $L/H = 20$ and $W/H = 20$. For simplicity, the results are computed without modeling the intersections as cross canyons or long canyons (as denoted by “Case 1” and “Case 2” in Chapter 5, respectively). Because the percentage of the UCL volume which is an intersection is increasingly small with increasing values of $L/H$ and $W/H$, this simplification is justified. The results are shown in Figure 6-23. Each surface in this figure represents a particular value of street canyon aspect ratio, ranging from $H/L_{int}=2-8$, where $W_{int}/L_{int} = 1$. These results could be used by urban designers to predict the implications of changing street width or building height on an orthogonally gridded neighborhood. Policy makers could use these results to set limits on street canyon aspect ratios for new neighborhoods.

The surfaces are projected onto the $L/H,(C_{ss}u_n)/(S H_s)$–plane in Figure 6-24, and are colored by aspect ratio to show the effect of varying $L/H$ on the dimension-
less concentration. These results show that increasing $L/H$ leads to an increase in dimensionless concentration as discussed for $H/L_{int} = 2$ in Chapter 5. A useful piece of insight to urban designers could be that this effect is much less pronounced than the effect of increasing $H/L_{int}$ on the dimensionless concentration. Therefore, if an urban designers goal is to decrease this dimensionless concentration metric, decreasing the street canyon aspect ratio a small amount will be more effective than decreasing $L/H$, even if the decrease in $L/H$ is relatively large in many cases. This is especially true at larger values of $H/L_{int}$. These insights are relevant for this range of $L/H$.

Similarly, the surfaces in Figure 6-23 are projected onto the $W/H, (C_{ss} u_0)/(S H_s)$-plane in Figure 6-25. These results indicate that increasing $W/H$ leads to a reduction in dimensionless concentration, which is consistent with the discussions presented in Chapter 5 for $H/W_{int} = 2$. The results show that if an urban designer or policy makers goal is to decrease the dimensionless concentration metric, it will be more
effective to decrease the street canyon aspect ratio a small amount throughout the neighborhood than to increase \( W/H \) unless this change is relatively large. Decreasing the street canyon aspect ratio is especially effective towards decreasing the dimensionless concentration at larger values of \( H/L \). The results in Figures 6-23–6-25 show that in an orthogonally gridded neighborhood of constant height, urban designers and policy makers should above all else minimize the street canyon aspect ratios when possible to reduce the dimensionless concentration. Further relevant examples and extensions of this approach will be presented in Chapter 9.

The results in Figures 6-23-6-25 are non-dimensionalized by the magnitude of the near-ground volumetric source, \( S \), as discussed in Section 4.2. In these simulations, the aspect ratios were increased by increasing the building heights, \( H \), and the other length scales, including \( H_s \) were kept constant. A crude, but perhaps more realistic estimate of source magnitude is that it is linearly related to population density. Assume that population density is linearly related to built volume per unit area, \( \beta \),

Figure 6-24: Surfaces of \((C_{ss} u_s)/(S H_s)\) for \( W/H \) vs. \( L/H \) projected onto the \( L/H, (C_{ss} u_s)/(S H_s)\)-plane for various values of \( H/L \), \( W/L = 1 \).
and the source, $S$, used for all of these simulations was set to $S_2$, the source size appropriate for $H/L_{int} = 2$. With the population density assumption, the source for any value of $H/L_{int}$, $S_i$, would be equal to

$$S_i = S_2 \left( \frac{\beta_i}{\beta_2} \right), \quad (6.4)$$

where $\beta_i$ is the ratio of built volume to plot area for $H/L_{int} = i$, and $\beta_2$ is the ratio of built volume to plot area for $H/L_{int} = 2$. For the work in this chapter, Equation 6.4 reduces to

$$S_i = S_2 \left( \frac{H_i}{H_2} \right), \quad (6.5)$$

where $H_i$ is the height of the buildings when $H/L_{int} = i$, and $H_2$ is the height of the buildings when $H/L_{int} = 2$. The magnitude of the dimensionless concentrations in the idealized, infinite street canyons in Figure 6-22 can be modified to reflect how the actual concentration would vary with aspect ratio if the source were varied as
in Equation 6.5. This is accomplished by modifying the data in Figure 6-22 using dimensional reasoning. Section 4.2 proves that the data in Figure 6-22 is equivalent to both sides of the following equation:

\[
\frac{C_{ss2} u_s}{S_2 H_s} = \frac{C_{ssi} u_s}{S_1 H_s}, \tag{6.6}
\]

where \( C_{ss2} \) is the steady state concentration in the UCL based on the constant source, \( S_2 \) (based on the approach described in Section 6.3) and \( C_{ssi} \) is the steady state concentration in the UCL assuming the source has been increased to \( S_i \). In practice, an urban designer or policy maker would be interested in the actual magnitude of \( C_{ssi} \) as a means of quantifying the effect of increasing the height of the buildings, assuming the source magnitude is related as in Equation 6.5. Equation 6.6 may be rearranged as:

\[
\frac{C_{ssi} u_s}{H_s} = \frac{C_{ss2} u_s}{S_2 H_s} S_i. \tag{6.7}
\]

For consistency with previous figures in this thesis, Equation 6.7 is made dimensionless by dividing by a constant source term, \( S_2 \), resulting in:

\[
\frac{C_{ssi} u_s}{S_2 H_s} = \frac{C_{ss2} u_s S_i}{S_2 H_s S_2}. \tag{6.8}
\]

Equation 6.8 is plotted against variations in \( H/L_{int} \) (for \( W_{int}/L_{int} = 1 \)) for the idealized infinite street canyons based on all of the aforementioned assumptions in Figure 6-26. This data is also plotted for the gridded neighborhoods described by Figure 6-1 at full UCL height as well as pedestrian height in Figures B-9 and B-10 in Appendix B.4. Figure 6-26 shows the effect on concentration of increasing the source size relative to the built volume as \( H/L_{int} \) is varied. The cross canyon results in Figure 6-26 may be compared to those calculated by Li et al. [2008b] because they used the height of the street canyon in the numerator of their dimensionless concentration which results in a scaling of the concentration similar to Equation 6.8. The concentration in \( H/L_{int} = 3 \) case is 3.5 times larger than in the \( H/L_{int} = 2 \) case in Figure 6-26, which matches well with the result in Li et al. [2008b]; they find the concentration in the
$H/L_{int} = 3$ case to be 4.6 times larger than the $H/L_{int} = 2$ case. The ratio of the results for $H/L_{int} = 5$ to $H/L_{int} = 2$ is 26 in this thesis, whereas Li et al. [2008b] find it to be 110. This discrepancy could be due to the line source simulated by Li et al. [2008b] in comparison to the near ground volume source used in the simulations in this thesis. The concentrations calculated close to the line source are much higher than those found anywhere else in the higher aspect ratio cross canyons, resulting in concentration contours that are not directly comparable to those used in this thesis. The general exponential trend in the results, however, is apparent in both the work in this thesis and in Li et al. [2008b]

Using the results in Figure 6-26, an urban designer would be able to understand the effect of increasing street canyon aspect ratio coupled with an estimate of the resulting increase in source magnitude on the concentration in the UCL. The surface plots in Figures 6-23–6-25 could be similarly scaled using Equation 6.8 to predict the effect of

Figure 6-26: \[\left(\frac{C_{ss} u_a}{S_2 H_s}\right) \times \left(\frac{S_1}{S_2}\right)\text{ vs. } H/L_{int}\text{ for idealized, infinite long canyons and cross canyons}\]
an increase in source magnitude on the concentration in the UCL at a neighborhood scale. With or without the effect of increased source magnitude due to increased built volume, these results show that increasing the building height will lead to increases in concentrations, and therefore reductions in air quality and heat removal from a near ground volumetric source. Therefore urban designers who are designing a dense orthogonally gridded neighborhood with buildings of a fixed height should reduce the aspect ratio of the street canyons to the extent that is possible within their design constraints. Other techniques which may be used to reduce concentrations further or in cases where a high aspect ratio is necessary are discussed in Chapters 7 and 8.

Figures 6-21, 6-22 and B-8, show that cross canyons have lower steady state concentrations than long canyons in all cases, and intersections may have concentrations in between these two values. These results could be used to influence design decisions, such as the placement of large windows or air intakes used for building ventilation. In these cases, the air with fewer scalars will be found in the cross canyons. To reduce the flux of scalars into buildings or near pedestrians, a designer may place fewer windows and air intakes in the façades along long canyons or may organize businesses so as to reduce street traffic in these canyons.

The results in Figures B-9 and B-10 are based on Equation 6.8, which is founded on simplified assumptions that neglect some urban realities. For example, as the density of the built volume increases, it is possible that some source magnitudes may eventually level-out or decrease, such as the number of vehicles on the road. This is because increased population density could lead to the introduction of an underground transit system as an alternative to cars, or an increase in pedestrian traffic rather than vehicle traffic due to an increased proximity of services. With this in mind, the figures based on Equation 6.8 act as more of an upper bound to the possible concentration in the UCL and at pedestrian height as street canyon aspect ratios (and sources) increase.

Another consideration, especially relevant in the cases where the infinite canyon results were used to predict orthogonally gridded neighborhood results, is that the time constants for reaching the steady state dimensionless concentrations increase
significantly with increasing street canyon aspect ratio. These time constants are shown for the idealized infinite canyon results shown in Figure 6-22 on a log-scale in Figure 6-27. As derived in Section 3.2, the time constant is inversely related to the characteristic velocity across the UCL-UBL interface. This means that the nearly exponential growth in time constants as a function of aspect ratio shown in Figure 6-27 suggests that the characteristic velocity across this interface decays exponentially with increasing street canyon aspect ratio. An exponential decay in the exchange between the air in the UCL and the UBL provides an intuitive way of understanding why the concentrations in the UCL increase so much with increasing aspect ratio. This is at least qualitatively consistent with the velocity contours shown for the various cross canyons in Li et al. [2008b], however they do not calculate a quantity for the characteristic velocity out of the cross canyon in their results.

The UCL volumes reach approximately 95% of their final value in $3\tau$ according to the work in Chapter 3 and Section 6.1. This means that the UCL volumes with aspect ratios larger than 5 reach their final value at times on the order of an entire day. Because sources such as HVAC waste heat, anthropogenic heat from pedestrians and pollution from traffic are not constant throughout the day, one may conclude that the magnitude of the dimensionless concentration in real street canyons will not reach that of the idealized, infinite street canyons, shown in Figure 6-22 in a single day. Consider a simplified model of pollutant release into an urban area: 12 hours of constant source in the UCL due to pedestrians, traffic and HVAC systems during business hours, followed by 12 hours of zero source releases in the UCL at night. This “square wave” source profile occurs each day (at least during the week) in most urban areas. Because the transient concentration grows like a first order step response over time, one may assume that so long as the time constant is less than three hours for a particular neighborhood, the 12 night hours without sources in the UCL will allow the concentration to decay to nearly zero before the next cycle begins. In the cases with time constants that are greater than three hours ($H/L_{int} > 5$), however, there will be residual concentration at the start of each day from the previous day. This will lead to an increase in the concentration each day at any particular time of day.
This type of reasoning, combined with knowledge of the likely source profiles in a neighborhood, could be used by policy makers to set limits on street canyon aspect ratios. They should try to ensure that the time constant of a particular neighborhood is well below the time constant threshold which would result in residual concentrations which would result in growing concentration values over multiple days.

Figure 6-27: $\tau$ vs. $H/L_{int}$ for idealized, infinite long canyons and cross canyons
Chapter 7

Building height variation

Variation in building height is common in urban areas. Figure 7-1 shows images of cities with little height variation. The building massing in these cities is significantly different than cities with a large amount of height variation, shown in Figure 7-2.

Figure 7-1: Aerial images of cities with little height variation, clockwise from top left: London, Amsterdam, Mexico City, Athens, Tehran, Barcelona
There has been little consideration of the effect of building height variation on parameters that may be of interest to urban designers. Hang et al. [2011] considered the effect of building height variance on the airflow in the UCL. They measured the airflow around a 9 x 12 orthogonally gridded building array in a wind tunnel. The array was oriented such that there were 9 buildings along the direction of the freestream flow field. This array had buildings with two distinct heights staggered in a checkerboard pattern: one of the heights was twice the width of the streets separating the buildings and the other height was 2.67 times the width of the streets separating the buildings. This is equivalent to a normalized standard deviation $\sigma_H/\bar{H}$ of 0.143. They found there to be greater lateral mean flow between the cross canyons and the long canyons in comparison to similarly laid out building arrays with constant building height. They also measured larger vertical mean flows into and out of the cross canyons upwind and downwind of the taller buildings, respectively, in comparison to building arrays of constant height. They noted that the downward vertical mean flow
in cross canyons upwind of tall buildings was larger in magnitude than the upward vertical mean flow in cross canyons downwind of tall buildings. They concluded that these enhanced vertical mean flows may bring clean air from the UBL into the cross canyons.

This work was complemented by the work of Hang and Li [2011] where similar arrays were studied with CFD using a $k - \epsilon$ turbulence model. The grid layout and checkerboard pattern of building heights were the same as in the work of Hang et al. [2011], however they also studied a case with 18 rows of buildings in the direction of the wind. They also simulated arrays with constant building height. In each of these simulations, they released a constant passive pollutant source uniformly within the UCL. They simulated the cases with two distinct buildings heights twice, once with the passive source released in the volume below the height of the taller buildings and once with the passive source released in the volume below the height of the shorter buildings. They compared the local mean age of air in these neighborhood layouts, $\bar{\tau}_p$, which is essentially $C_{ss}/S$ in the context of this thesis. Their definition of local mean age of air is limited to their case, however, where the source is released uniformly within the UCL. They studied how this parameter changes along the gridded array in the direction of the wind, and defined a unit volume consisting of a half of a long canyon (divided along the axis aligned with the wind), the half of an intersection downwind of the half long canyon and the half of a adjacent cross canyon (also divided along the axis aligned with the wind). This unit volume is some nominal height, $dz$, making it a thin horizontal slab. Despite the enhanced lateral and vertical mean flows, they found that this building array had similar mean ages of air as those of uniform height. They admit that more work needs to be done to draw conclusions about building height variance that may be used by urban designers.

Hang et al. [2012] performed wind tunnel experiments and CFD simulations with a $k-\epsilon$ turbulence model on building arrays similar to those used by Hang et al. [2011]. They extended that work by considering a greater range of two-height arrays, each with the same average building height but with more values of $\sigma_H/H$, specifically they studied $\sigma_H/H = 0 - 0.57$. They released passive pollutants uniformly into the
pedestrian level, meaning from 0-2 m. They used a metric, the normalized pedestrian purging flow rate to consider the results. This metric is non dimensional and is similar to the inverse of the non-dimensional metric used in this thesis ($C_{ss} \frac{u_a}{S H_s}$). Because they normalized their metric by the volumetric flow rate to make it non-dimensional, they end up with the length scale to be the length of the volume in question in the direction of the wind, rather than $H_s$. In many cases, these lengths and heights are constants, so the trends in their results should be comparable to those in this thesis.

Hang et al. [2012] concluded that mean flows are more important that turbulent diffusion for removing pollutants in the cases with building height variation. They also found that increasing the standard deviation of building heights increases the transport of passive pollutants due to increased vertical mean flow in the pedestrian zone. They note that these results are valid for only arrays that are similar to these ($< 1$ km in the direction of the wind).

The previous work discussed in this section has considered only two building heights, which is unrealistic in the context of an urban area. Additionally, the results of this work are tied to the fact that the UCL is of a fixed length in the direction of the wind. Much of the discussion in this previous work is related to how the concentration varies in the neighborhood along the direction of the wind. As discussed in Chapter 3, this approach is limiting and may not capture the essence of how the building geometry is affecting the mixing between the UCL and the UBL. To this end, the approach in this thesis is to consider more realistic building geometry to study the effect of building height variance on parameters of interest to urban designers, and this will be considered using a repeating neighborhood of buildings and periodic boundary conditions. Section 7.1 describes and justifies the domain used to study the relevant effects of building height variation. In Section 7.2 the transient non-dimensional concentration data at $t = 60$ s is presented and how the flow field in the UCL changes as the variation in building height is increased is discussed. Section 7.3 focuses on the steady state concentration data in the context of building height variation. The implications of the results for urban design are discussed in Section 7.4.
7.1 Domain

The repeating neighborhood-scale domain, shown in plan in Figure 7-3, was meshed and simulated as described in Section 3.1. The uniform hexahedral mesh was applied everywhere below and up to the height of the tallest building of each neighborhood. The data was post processed as discussed in Section 3.2. Each neighborhood-scale domain has 36 distinct buildings, and is repeated in both the $x$ and $y$-direction, as shown in Figure 3-2. The vertical dimension of the large volume above the buildings was set to five times the average building height, $H = 20$ m. This was increased to nine times the average building height in cases where the building height variance, $(\sigma_H)^2 \geq 2 \bar{H}$ because of the increased likelihood of a very tall building relative to the average building height.

The method for varying building height in this study was inspired by the existing building stock in London. United Kingdom census data divides the greater London area into Lower Layer Super Output Area (LLSOA) units which have an average population of 1500 with a standard deviation of 11 [Quinn et al., 2011]. Each LLSOA unit contains an average of 178 buildings spread over 0.49 km$^2$ of land. This is considered to be in the range of a neighborhood scale, defined in Section 3.3.3. Using the plan area density, average building height and other urban form measures for each LLSOA unit, Quinn et al. [2011] categorized the 5625 distinct neighborhoods into three different typologies using a statistical clustering technique. The typologies reflect the population density of London to some extent, where Type 1 LLSOA units are the most dense, Type 2 are in the middle, and Type 3 are the least dense. These LLSOA categorizations are presented on a map of London in Figure 7-4.

Figure 7-5 shows the probability density functions of building heights for each of the 5625 LLSOA units, colored by the type of neighborhood. Each line is plotted with some transparency so that more common areas are shown in a brighter color. The Type 1 LLSOA units appear to have the widest spread of building heights, as well as the tallest buildings. The Type 2 and Type 3 LLSOA units have peaks at $H \approx 20$ m, and the Type 2 LLSOA units have a secondary peak at $H \approx 14$ m. The
peaks in Figure 7-5 suggest that there is a particular building height that is common in the Type 3 LLSOA units, and there is little deviation from that building height. In the Type 2 LLSOA units, there are one or two common building heights in many of the LLSOA units, with little variation outside of those two peaks. In the Type 1 LLSOA units, however, there appears to be more spread in building height, both above and below the main peak, which is at $H \approx 20$ m.

Figure 7-6 shows the probability distribution function for every building in each of the three LLSOA types. The trends are similar to those shown for each specific LLSOA unit in Figure 7-5. For this thesis, the Type 1 LLSOA units are most relevant.
Figure 7-4: Map of London showing the grouping of the LLSOA divisions in three clusters [Quinn et al., 2011]

Figure 7-5: Probability density of building heights for each LLSOA unit
because this thesis is focused on dense urban areas. The building heights for this case are more similar to a normal distribution than a uniform distribution, and there appears to be little skew in the data. To this end, the building heights simulated for a particular neighborhood in the height variation study were approximately normally distributed. The 36 building heights were determined by randomly generating integers from a normal distribution with a fixed value for variance, centered at $H = 20$ m. Next the second central moment of the 36 integers was calculated:

$$ (\sigma_H)^2 = \frac{1}{N} \sum_{i=1}^{N} (H_i - \bar{H})^2, $$

(7.1)

where $N$ is the number of building heights, in this case 36, $\sigma^2$ is the building height variance and $H_i$ is one of the building heights in Figure 7-3. If the second central moment from Equation 7.1 was exactly equal to the building height variance, then the building heights were deemed an acceptable neighborhood distribution. Two neighborhoods were generated for each of the following values of $(\sigma_H)^2$: 2, 4, 6, 8, 10, 12, 14, 16, 25, 36, 49, 64, 81 and 100 m². For the work in this thesis, these values
are presented in terms of standard deviation and normalized by the average building height, \( \sigma_H / \bar{H} \), resulting in: 0.07, 0.10, 0.12, 0.14, 0.16, 0.17, 0.19, 0.20, 0.25, 0.30, 0.35, 0.40, 0.45 and 0.50. Histograms showing the distribution of building heights for each neighborhood are shown in Figure 7-7, where the x-axes are building height in meters, and the y-axes are the percentage of buildings in the neighborhood with that particular height. The bin sizes for the histograms were set to 1 m for all cases. Orthographic images of one of the \((\sigma_H)^2 = 4 \text{ m}^2\) and \((\sigma_H)^2 = 25 \text{ m}^2\) neighborhood domains are shown in Figures 7-8(a) and (b), respectively to qualitatively show the difference in massing between the histogram data in Figures 7-7(b) and 7-7(i).

Each neighborhood scale domain was simulated four times, each with different incident wind directions: +x, +y, −x and −y. With two neighborhoods for each value of \((\sigma_H)^2\), this results in eight distinct simulations for a single value of \((\sigma_H)^2\). The dimensionless concentration is computed for each of these cases at both a neighborhood scale and a street canyon scale.
Figure 7-7: Percent of buildings vs. Building height [m] for: (a) \((\sigma_H)^2 = 2 \text{ m}^2\), (b) \((\sigma_H)^2 = 4 \text{ m}^2\), (c) \((\sigma_H)^2 = 6 \text{ m}^2\), (d) \((\sigma_H)^2 = 8 \text{ m}^2\), (e) \((\sigma_H)^2 = 10 \text{ m}^2\), (f) \((\sigma_H)^2 = 12 \text{ m}^2\), (g) \((\sigma_H)^2 = 14 \text{ m}^2\), (h) \((\sigma_H)^2 = 16 \text{ m}^2\), (i) \((\sigma_H)^2 = 25 \text{ m}^2\), (j) \((\sigma_H)^2 = 36 \text{ m}^2\), (k) \((\sigma_H)^2 = 49 \text{ m}^2\), (l) \((\sigma_H)^2 = 64 \text{ m}^2\), (m) \((\sigma_H)^2 = 81 \text{ m}^2\), (n) \((\sigma_H)^2 = 100 \text{ m}^2\)
Figure 7-8: (a) Domain with building height variance of $\sigma_H^2 = 4 \text{ m}^2$; (b) Domain with building height variance of $\sigma_H^2 = 25 \text{ m}^2$
7.2 Transient results and relevant physics for variations in building height variance

When calculating the average concentration at a neighborhood or street canyon scale for the domains with the height distributions shown in Figure 7-7, the height of the UCL is not as obvious as in the neighborhoods discussed in Chapters 5 and 6 with buildings of constant height. The height of the UCL-UBL interface was set to \( z/H = 0.5 \) to calculate the concentration in the UCL, shown in equation form as:

\[
C = \frac{1}{V} \int_{x} \int_{y} \int_{z/H=0.5} c(x, y, z) \, dx \, dy \, dz, \tag{7.2}
\]

for all of the work in this chapter. For the cases simulated, with the height distributions shown in Figure 7-7, this definition of the UCL-UBL interface is at or above roof level of the shortest building in each neighborhood for \( \sigma_H/H \leq 0.25 \). The volumes directly above buildings shorter than \( z/H = 0.5 \) were not counted as part of the UCL volume. This means that the volume of the UCL in each simulation is equal.

The dimensionless concentrations at \( t = 60 \) s, averaged over the volume of the UCL as defined in Equation 7.2, are plotted against the normalized standard deviation in building heights, \( \sigma_H/H \), in Figure 7-9. Because eight cases were simulated for each value of \( \sigma_H/H \), the results are presented as box plots, where the box edges are specified as the 25\(^{th}\) and 75\(^{th}\) percentiles, the central line in the box is the median, and the whiskers extend to the minimum and maximum value that is not an outlier. Dimensionless concentrations are considered to be outliers if

\[
\frac{C u_a}{S H_s} > Q_3 + 1.5 (Q_3 - Q_1) \tag{7.3}
\]

or

\[
\frac{C u_a}{S H_s} < Q_1 - 1.5 (Q_3 - Q_1) \tag{7.4}
\]
where $Q_1$ is the 25th percentile and $Q_3$ is the 75th percentile. Additionally, an “x” marks the mean value. Using Equation 5.3, after $t = 60$ s the dimensionless concentration in the UCL would be 60 for these domains, assuming none has been removed to the UBL. As $\sigma_H/H$ increases, the dimensionless concentration at $t = 60$ s decreases, until $\sigma_H/H = 0.25$, after which the trend becomes more horizontal.

![Graph](image)

Figure 7-9: $(C u_a)/(S H_a)$ vs. $\sigma_H/H$ at $t = 60$ s, averaged over the UCLs of each neighborhood

This trend can be explained by considering the concentrations at a street canyon scale, shown in Figure 7-10. In this graph, the outliers are shown as “+” symbols in the color of box plot associated with the particular UCL volume. The data at $\sigma_H/H = 0$ is similar to the $t = 60$ s in Chapter 5 which has larger concentrations in the long canyons and smaller concentrations in the cross canyons relative to the average neighborhood concentration. This is due to the effect of the three-dimensional vortices in the cross canyons found in neighborhoods of constant height, discussed in Section 5.1.1. For the $0 < \sigma_H/H \leq 0.25$ cases, the long canyon concentrations decrease with increasing $\sigma_H$ and the intersection concentrations decrease to
a lesser extent. On average, the cross canyon concentrations remain approximately constant as $\sigma_H$ is varied. As in the $\sigma_H/\bar{H} = 0$ case, the cross canyons have lower concentrations than the long canyons on average, however the difference between the average long canyon and average cross canyon concentration is much smaller in these cases than in the $\sigma_H/\bar{H} = 0$ case. The average intersection concentrations for the $0 < \sigma_H/\bar{H} \leq 0.25$ cases are lower than both the cross canyons and the long canyons, unlike the $\sigma_H/\bar{H} = 0$ case. For $0.25 < \sigma_H/\bar{H} \leq 0.50$ cases, the long canyon, cross canyon and intersection dimensionless concentrations are approximately constant as $\sigma_H$ increases. The average long canyon and cross canyon dimensionless concentrations are of similar magnitude, and the intersection concentrations are lower. These trends can be explained by considering the mean flow fields.

![Graph](image)

Figure 7-10: $(C_{u_0})/(S H_s)$ vs. $\sigma_H/\bar{H}$ at $t = 60$ s, averaged over the UCL volumes of each neighborhood.

The flow fields in these cases are more complicated and varied than those studied in Chapters 5 and 6 because the fluid in each street canyon volume may be affected by the variation in building heights upwind, downwind and in the lateral direction.
Attempting to understand the reasons for the flow structures in each street canyon volume would be a time consuming process due to the number of unique cases studied: 14 non-zero values of $\sigma_H/H$, eight neighborhoods for each value of $\sigma_H/H$, three different types of street canyon volumes, 36 instances of each type of street canyon volume per neighborhood, resulting in 12096 unique street canyon volumes to study. In this thesis, the changes in the flow field due to changes in $\sigma_H/H$ are assessed at neighborhood and neighborhood-averaged street canyon scale rather than at a single street canyon scale as in Chapters 5 and 6.

To that end, to visualize the flow fields at a neighborhood scale, each neighborhood is divided into six equal sub-neighborhood volumes, shown schematically with six distinct colors in a plan view of the domain in Figure 7-11. These volumes each measure 30 m in the $y$-direction when the incident wind is in the $x$-direction. Figure 7-12 shows streamlines released from $x,y$-planes of constant height for a subset of the neighborhoods studied, oriented so that the incident wind is in the $x$-direction. Each plane spans the entire $x$ and $y$ dimensions of the volumes shown in Figure 7-11 and each streamline is colored by the plane it is released from. Forty three-dimensional streamlines are generated on each plane. The streamlines used to generate the results in Figure 7-12 are released from planes at $z/H = 0.25$, centered vertically in the UCL volume defined by Equation 7.2.

In Figure 7-12(a), the $\sigma_H/H = 0$ case, the colored streamlines remain in the volume of the sub-neighborhood, defined in Figure 7-11, from which they are released. The flow field is as expected based on the work in Chapter 5: the flow in the cross canyons is dominated by vortical structures, and the flow along the long canyons is aligned with the wind. The streamlines remain below roof level for the most part, meaning there is little mean vertical flow from this plane to the section of the UBL above $z/H = 1$. For the $\sigma_H/H > 0$ cases, shown in Figures 7-12(b)–(f), there are many streamlines which move vertically into and out of the UCL as defined by Equation 7.2. This is evidenced by the presence of streamlines above roof level of most buildings. These vertical mean flows are qualitatively consistent with the findings of Hang et al. [2011]. These streamlines will transport scalars
vertically out of the UCL and towards the UBL. The scalars will be mixed into the UBL by turbulent diffusion. Qualitatively, this effect seems increasingly pronounced as $\sigma_H/\bar{H}$ increases, as evidenced by the density of streamlines above roof level in Figures 7-12(a)–(f). This may explain the decrease in the neighborhood averaged non-dimensional concentration shown in Figure 7-9. The leveling off of the trend at $\sigma_H/\bar{H} \geq 0.25$ may be explained by the distribution of building heights in these cases: though a scalar may be transported along a streamline above roof level, as $\sigma_H/\bar{H}$ increases, the chances of this streamline impinging on a tall downwind building also increases, resulting in the reentry of the scalar to the UCL. At larger values of $\sigma_H/\bar{H},$
Figure 7-12: Streamlines released from $z/H = 0.25$, colored by the neighborhood division from which they were released.
these above-roof-level scalars may occur at a lower absolute height because there is a larger number of buildings with heights less than the UCL-UBL interface.

Additionally, for the $\sigma_H/\bar{H} > 0$ cases, the three-dimensional streamlines cross the lateral boundaries of defined volumes in Figure 7-11 as evidenced by the variety of colors in each defined volume in Figures 7-12(b)–(f). These lateral mean flows are qualitatively consistent with the results in Hang et al. [2011]. This effect is increasingly pronounced with increasing value of $\sigma_H/\bar{H}$. This lateral mean flow is responsible for the convergence of the average long canyon and cross canyon concentrations as shown in Figure 7-10. This leads to a more well mixed neighborhood at street canyon scale than those with $\sigma_H/\bar{H} = 0$, discussed at length in Chapters 5 and 6 (example shown in Figure 7-12(a)). This increase in lateral mixing with increasing $\sigma_H/\bar{H}$ can be seen qualitatively by considering each sub-neighborhood, and approximating the lateral distance of each streamline in that volume from its origin. For example, the yellow sub-neighborhood volume in Figure 7-12(f) with $\sigma_H/\bar{H} = 0.5$ seems to have some streamlines that originated from the purple sub-neighborhood volume, which is three sub-neighborhood volumes away. The neighborhood also has streamlines from the blue and red sub-neighborhood volumes, which are two sub-neighborhood volumes away. This may be compared to the $0 < \sigma_H/\bar{H} \leq 0.25$ cases shown in Figures 7-12(b)–(d) which rarely have streamlines in a sub-neighborhood volume originating from more than one sub-neighborhood volume away.

Figure 7-13 shows the concentrations averaged over pedestrian height ($0 < z < 2$ m) for the street canyon volumes at $t = 60$ s. The trends are similar to those averaged over the UCL, shown in Figure 7-9. These results may be understood by considering the streamlines released from a horizontal plane in the center of the pedestrian height volume, $z = 1$ m, shown in Figure 7-14. These streamlines are colored by the sub-neighborhood volume from which they were released, shown in Figure 7-11.

Similarly to the UCL-averaged results, the neighborhoods seem to have increased lateral mixing with increasing $\sigma_H/\bar{H}$ as evidenced by convergence of the cross and
long canyons cross canyons intersections

Figure 7-13: \((C u_a)/(S H_s)\) vs. \(\sigma_H/\overline{H}\) at \(t = 60\) s, averaged over pedestrian height UCL volumes of each neighborhood, from \(z = 0 - 2\) m

long canyon concentrations in Figure 7-13, as well as the increasing variation of colors in each sub neighborhood volume as \(\sigma_H/\overline{H}\) increases in Figure 7-14.

The implications of the variation in the \(t = 60\) s concentration data with building height variation, shown in Figures 7-9, 7-10 and 7-13, on urban design applications will be discussed in Section 7.4.
Figure 7-14: Streamlines released from $z = 1$ m, colored by the neighborhood division from which they were released.
7.3 Steady state results and relevant physics for variations in building height variance

The steady state dimensionless concentrations, averaged over the UCL volume as shown in Equation 7.2 are plotted against the normalized standard deviation in building heights in Figure 7-15. The box plots show the spread of the results across the eight neighborhoods for each $\sigma_H/H > 0$ case using the box plot definitions defined in Equations 7.3 and 7.4 and discussed in Section 7.2. Similar to the transient results shown in Figure 7-9, as $\sigma_H/H$ increases the steady state dimensionless concentration decreases for $\sigma_H/H \leq 0.25$. Beyond this threshold, the trend flattens. The decrease in concentration for $\sigma_H/H \leq 0.25$ is due to an increase in mean vertical flow with increasing height variation as discussed in Section 7.2 and evidenced by the streamlines above roof level in Figure 7-12. At steady state, the slope of the decreasing portion of the trend is larger than at $t = 60$ s, resulting in neighborhoods with $\sigma_H/H \geq 0.25$ having almost a factor of two reduction in dimensionless steady state concentration relative to the $\sigma_H/H = 0$ case. The horizontal part of the trend may be explained by competing effect of the increased likelihood of a much taller building downwind of an above roof level streamline which in some cases will lead to reentry of the streamline into the UCL as explained in Section 7.2.

The street canyon scale steady state concentration results are shown for the UCL volumes in Figure 7-16. The $\sigma_H/H = 0$ results show that long canyons have higher concentrations than cross canyons for reasons discussed in Chapter 5 and Section 7.2. The $\sigma_H/H > 0$ results suggest that increasing the building height variance leads to well mixed neighborhoods due to lateral mean flows among the UCL volumes, shown with streamlines in Figure 7-12. The three trends for each of the UCL volumes generally follow the trend of the UCL-averaged result shown in Figure 7-15 for $\sigma_H/H > 0$. The pedestrian height steady state dimensionless concentration results are shown in box plots in Appendix B.5, averaged over the UCL and over the UCL volumes in Figures B-11 and B-12, respectively. The trends are similar to those found when
Figure 7-15: \( \frac{(C_{ss} u_a)}{(S H_s)} \) vs. \( \frac{\sigma_H}{\bar{H}} \), averaged over the UCLs of each neighborhood averaging over the UCL as per Equation 7.2. The implications of the results in this section will be discussed in Section 7.4.
7.4 Implications

Varying building heights within an orthogonally gridded neighborhood aligned with the wind leads to an overall decrease in the dimensionless concentration in the UCL. Though the work in this chapter does not extend to how this effect changes with variations in $L$, $W$ or $H$, it is apparent from the streamlines in Figures 7-12 and 7-14 as well as knowledge of how air flows in narrower and longer canyons (from Chapters 5 and 6) that the results are qualitatively applicable to other cases. Urban designers and policy makers may be interested in the outcome that a small increase in normalized building height standard deviation from $\sigma_H/H = 0$ results in a steep decrease in the dimensionless concentration in the UCL at small times and at steady state for both the entire UCL and at pedestrian height. This is due to an increase in vertical mixing between the UCL and the UBL in comparison to neighborhoods with buildings of a constant height. This is evidenced by the streamlines above roof
level shown in Figures 7-12 and 7-14 as well as the box plots in Figures 7-10 and 7-16. This result could be used by policy makers to set height requirements for new buildings in a particular neighborhood. They could intentionally choose heights that would increase building height variation, improve mixing between the UCL and the UBL and reduce the average pollutant concentrations in the UCL.

Additionally, increasing the normalized building height standard deviation from $\sigma_H/\bar{H} = 0$ leads to an increase in lateral mixing among the UCL volumes as evidenced by the streamlines crossing into various sub-neighborhoods in Figures 7-12 and 7-14 as well as the convergence of the long canyon, cross canyon and intersection box plots with increasing building height variation shown in Figures 7-13 and B-12. This result would be useful to urban designers who are interested in avoiding a neighborhood with a certain type of UCL volume having an average concentration that is much higher than the average concentration in the UCL. For example, the long canyons in the case where $\sigma_H/\bar{H} = 0$ have a much higher dimensionless concentration than the average dimensionless concentration in the UCL in that case as shown in Figures 7-15 and 7-16, whereas each UCL volume type in the cases with $\sigma_H/\bar{H} \geq 0.25$ has an average dimensionless concentration that is closer to the average UCL concentration. This could be applied by an urban designer is trying to locate a series of bus stops in urban areas which will have frequent, short periods of emissions from idling buses. The lateral mixing and mean horizontal and vertical flows lead to lower neighborhood-scale time constants than the cases of constant height which rely primarily on turbulent exchange to remove scalars from the UCL to the UBL. Therefore, the designer may qualitatively consider the steady state results and should determine that the bus stops should be located along the cross canyons when possible if there is no building height variation because these volumes are best at removing passive scalars and maintaining a relatively low dimensionless concentration at pedestrian height. When $\sigma_H/\bar{H} > 0$, it is less important to design the bus stop placement around a particular UCL volume because of the lateral mixing among the various volumes. If the locations are placed randomly, on average the concentration results for pedestrians will follow the trends in Figure B-12. In cases with building height variation, the designer should consider
further analysis to ensure that each particular bus stop is not placed in a canyon with a particularly high dimensionless concentration. The jitter plot in Figure 7-17 presents the non-dimensional steady state concentrations at pedestrian height in each street canyon studied in this chapter. Comparing these results to the those presented in Figure B-12, it is clear that some amount of individual street canyons will have significantly higher concentrations than the $\sigma_H/\bar{H} = 0$ case. These high concentration canyons are possible at all values of $\sigma_H/\bar{H} > 0$ as seen in the jitter plot. Though these small scale considerations are out of the scope of this thesis, it may be possible to use some fluid mechanical insight based on the work in Chapters 5 and 6 to predict canyons with particularly high concentrations. For example, a tall building located directly downwind of another tall building would result in a cross canyon with a larger aspect ratio than the average in the neighborhood, and the work in Chapter 6 suggests that this would result in a larger dimensionless concentration in this canyon.

The rate of decrease of the dimensionless concentration decreases with increasing normalized building height standard deviation until the magnitude of the dimensionless concentration levels off. This may be explained by the very tall buildings which will be statistically likely to be present in large height variation neighborhoods. These buildings could potentially block upwind species from being removed to the UBL over rooftops rather than simply improving lateral mixing. Urban designers should choose, when possible, to create neighborhoods with some height variation rather than a fixed height. Small increases in $\sigma_H/\bar{H}$ could be designed in such a way that they have little to no effect on the built volume per unit land area, while having a large effect on the dimensionless concentration in the UCL. Assuming there are policies in place which set the maximum building height, large values of $\sigma_H/\bar{H}$ could lead to decreases in built volume per unit land area in high density areas.

A potential drawback to increased height variation would be in the case of an accidental or intentional release of a toxic chemical into the UCL. Though the chemical would be removed more quickly into the UBL in neighborhoods with height variation (the lower time constants from lateral and mean vertical flows for a constant source
are the same time constants that would be used to calculate the decay of concentration due to a release in the form of a delta function), the affected area, which must be known by the first responder to quarantine and treat those affected by the release, would be less obvious than the $\sigma_H/\overline{H} = 0$ case as evidenced by the increasing lateral travel in the streamlines released from pedestrian height and shown in Figures 7-14.
Figure 7-17: \( (C_{ss} u_o)/(S H_o) \) vs. \( \sigma_H/\bar{H} \), averaged over the individual street canyons for each neighborhood, from \( z = 0 \text{--} 2 \text{ m} \)
Chapter 8

Other geometries as case studies

Chapters 5–7 focus on gaining a deeper understanding of why certain geometric parameters in orthogonally gridded neighborhoods improve exchanges between the UCL and the UBL, which results in lower concentrations in street canyons and in the neighborhood overall. Because of the goal to develop an understanding of the physics involved in the relevant fluid mechanical processes, the geometries in the previous chapters are necessarily simple. This chapter focuses on case studies of somewhat more realistic urban forms. Section 8.1 considers the effect of parks and open areas of different shapes and sizes on the dimensionless concentrations at pedestrian height. Section 8.2 is a case study inspired by Singaporean urban design. This section compares the dimensionless concentration at pedestrian height around various clustered building layouts rather than urban form based on an orthogonal grid. These studies do not have as much discussion of the relevant physical processes responsible for the results as the work in Chapters 5–7, and thus should only be applied to disparate geometries with caution.

8.1 Parks, a case study

Parks or open areas replacing partial, complete or multiple city blocks are common in orthogonally gridded cities, as shown in Figure 8-1. Much of the previous work
studying parks and open areas in urban neighborhoods focuses on the effects of the park and vegetation on the temperatures within the UCL (park effect) [e.g. Givoni, 1991; Spronken-Smith, 1994; Jansson et al., 2007] or the process by which the thermal characteristics of parks induce airflow within the UCL (park breeze) [e.g. Eliasson and Upmanis, 2000; Jansson et al., 2007]. These studies do not consider how parks affect airflow in the forced case, when the flow in the UCL is driven by the freestream flow field, rather than the thermal difference between the park and the urban area.

In this thesis, a case study inspired by park geometries shown in Figure 8-1 is performed. The study aims to determine how the size and orientation of parks in orthogonally gridded neighborhoods affect the steady state dimensionless concentration at pedestrian height. While this work is not comprehensive, in that it is not a parametric study combined with physically based discussions like those in Chapters 5–7, the results and outcomes of this work will give a starting point for urban designers to understand how parks affect street canyon and neighborhood scale concentrations.

Figure 8-1: Parks within repetitive gridded neighborhoods, clockwise from top left: Santa Monica, San Francisco, Barcelona, Portland (OR), Savannah, Philadelphia (Adapted from: Jacobs [1993])
The park layouts under consideration are shown in Figure 8-2. The square buildings surrounding these parks are of dimensions: 20 m x 20 m x 20 m. These parks are centered in a 6 x 6 grid of buildings of the same size as those shown in Figure 7-3. The parks are modeled as buildings with $H = 0$ m. These park domains were meshed and simulated as described in Section 3.1. As in the previous work in this thesis, a constant volumetric source release was placed in the lowest grid cell of the long canyons, cross canyons and intersections to emulate traffic and other near ground sources. The source was not placed in the park areas denoted by the green pattern in Figure 8-2. The results were post processed as described in Section 3.2.

The dimensionless steady state concentration averaged over the long canyons, cross canyons and intersections from $z = 0$–2 m is a neighborhood-scale measure of the dimensionless steady state concentration at pedestrian height. This pedestrian height data is further averaged for the cases in Figure 8-2 with the same number of
parks (denoted by the number in their case name in Figure 8-2). These averaged results are shown in Figure 8-3. This shows that there is a general trend of increased mixing from the UCL to the UBL as the number of unit park areas increases. This trend is examined in greater detail by looking at the average non-dimensional steady state concentration at pedestrian height in each type of UCL volume, shown in Figure 8-4. In general, much of the reduction in concentration at pedestrian height with increasing number of park area units is seen in the long canyons. As expected, the cross canyons have lower concentrations than the long canyons, as discussed in Chapter 5. Urban designers may be interested to learn that adding parks or open areas to a design will reduce overall neighborhood concentrations via reductions in long canyon concentrations. If the goals of a new neighborhood design are to reduce overall pedestrian height concentrations as well as to reduce concentrations in areas prone to high concentrations, adding one or more park area units could be a useful design technique.
To understand which park configurations are more beneficial in reducing overall pedestrian height concentrations, Figure 8-5 shows the average steady state concentration at pedestrian height for each of the park configurations shown in Figure 8-2. Additionally, Figure 8-5 shows the bulk averaged concentration for the $\sigma_{H}/\overline{H} = 0.5$ neighborhoods from Chapter 7. Each of the eight neighborhoods in the $\sigma_{H}/\overline{H} = 0.5$ cases had a single building at $H = 0$ m, which is equivalent to one park area unit. Figure 8-5 shows that the “Long” configurations, which have multiple park units in a row along the direction of the wind, tend to have lower bulk averaged steady state concentrations at pedestrian height than other configurations. Configurations where the park areas cut into buildings rather than taking up an entire block area tend to have higher concentrations than the average values shown in Figure 8-3, regardless of if they are aligned with the wind or not. This information could be useful to an urban designer trying to decide the layout of a park system within a neighborhood. The $\sigma_{H}/\overline{H} = 0.5$ cases have much lower bulk averaged steady state concentration.
at pedestrian height on average than the comparable constant height case with one park, “1 Square.” The $\sigma_{H}/\overline{H} = 0.5$ cases also have lower concentrations than even the cases with four parks. This suggests that varying the heights of buildings in a gridded neighborhood could be a more effective way of reducing steady state concentration levels at pedestrian height than adding parks in a neighborhood of buildings with constant height. Additionally, varying the building heights does not reduce the ratio of built volume per unit land area, whereas replacing buildings with parks does reduce this ratio. A reduction in this ratio will lead to a reduction in the capacity of residents and services that can be located in a particular urban area.

Figure 8-5: $(C_{ss}, u_a)/(S H_s)$ vs. park area unit configuration, averaged over $z = 0 - 2$ m

Figure 8-6 shows the average non-dimensional steady state concentration at pedestrian height within each type of UCL volume. For the constant height cases, the concentrations in the intersections and cross canyons are relatively constant as park

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configuration changes. It is apparent that the “Long” cases (with multiple parks aligned with the wind) have lower overall steady state concentrations at pedestrian height specifically due to a reduction in long canyon concentrations. This information may be useful to urban designers interested in reducing the concentration in the areas prone to higher concentration in gridded neighborhoods (i.e. long canyons). Designing uniform height neighborhoods with a series of parks aligned with the dominant wind direction would lead to a reduction in the neighborhood average concentration at pedestrian height, as well as a reduction in concentration in the areas which need it most. As discussed in Chapter 7, the cases with $\sigma_H/\bar{H} = 0.5$ result in a well-mixed pedestrian height volume on average. Though the average concentration in the cross canyons of the $\sigma_H/\bar{H} = 0.5$ cases is greater than the cross canyon concentrations in the park cases, the average concentration in the long canyons is drastically reduced, nearly to the level of the cross canyon concentrations. Therefore, urban designers who are interested in reducing concentrations in areas prone to high concentration may find varying building height to be more appropriate than adding parks in neighborhoods with buildings of constant height. While this comparison has been made for the $\sigma_H/\bar{H} = 0.5$ cases, which each have one “Park” (building lot where $H = 0$ m), comparing Figures B-11 and B-12 with Figures 8-5 and 8-6 show that a building height standard deviation of only $\sigma_H/\bar{H} = 0.1$ will result in neighborhoods with lower average pedestrian height concentrations than the uniform height neighborhoods with four parks. Additionally the cases with building height variation are more well mixed among the UCL volume types than the park cases with uniform building height.

Figure 8-7 shows the steady state concentrations at a street canyon scale for the park cases as well as the $\sigma_H/\bar{H} = 0.5$ cases. The jitter plot shows that there is an increased variation in the concentrations among each UCL volume type as the number of park area units increases. The concentration variation is especially apparent in the long canyons. The long canyon data has an approximately constant maximum concentration among all park cases as well as a large amount of spread, showing some long canyons to have up to 75% lower steady state concentrations than the “0” park case. This data is more clustered by UCL volume type than the $\sigma_H/\bar{H} = 0.5$ cases,
which seem to be well-mixed neighborhoods. There are a few (<4%) UCL volumes with larger steady state concentrations at pedestrian height in the $\sigma_H/\bar{H} = 0.5$ cases than the maximum street canyon concentrations in any of park cases. The majority of the data for street canyons in the $\sigma_H/\bar{H} = 0.5$ cases, however, are clustered near the cross canyon and intersection data from the park cases. Additionally, there are many street canyons in the height variation cases with lower concentrations than any street canyon in any of the park cases. There is no obvious pattern to the height variation data, it is simply a well-mixed set of neighborhoods with lower overall concentration than any of the park cases. As in the height variation cases discussed in Chapter 7, it will be important for urban designer to perform or request more detailed analysis when designing pedestrian areas in neighborhoods with parks to ensure areas with
high pedestrian traffic are not in the UCL volumes with much higher than average concentrations.

Figure 8-7: \( \frac{(C_{ss} u_a)}{(S H_x)} \) vs. park area unit configuration, averaged over each street canyon volume from \( z = 0 - 2 \) m
8.2 Building clusters, a case study

Previous work in this thesis has focused exclusively on high-density, repetitive, orthogonally gridded neighborhoods. Another type of geometry used for high density urban areas, herein referred to as building clusters, is characterized by neighborhoods made up of tall buildings clustered on large plots of land. These neighborhoods tend to have a larger fraction of open area to plot area for the same fraction of built volume to plot area. These geometries are typical of neighborhoods in Singapore; examples are shown in Figure 8-8.

Leung [2011] categorized the evolution of Singaporean building clusters into five generations as a means of summarizing how built form in Singapore has changed with time. Figure 8-9 shows five typical cluster layouts for each of the five generations. He simplified the building geometries from the typical cluster layouts in Figure 8-9 into four representative building types, shown in Figure 8-10. He then created generic layouts using these simple buildings to compare the daylighting performance of both the building types and the layouts using solar simulations.

Zhang et al. [2012] also took the approach of simplifying Singaporean building cluster geometry to perform a solar analysis case study. This group focused on the
dense, recent construction in Singapore, known as the new towns, rather than the historical approach taken by Leung [2011]. Their simplified urban geometries are shown in Figure 8-11. These simulations retain more geometric detail than those geometrics studied by Leung [2011] in Figure 8-10.

Inspired by these two studies, this thesis focuses primarily on the cluster layouts from the study performed by Zhang et al. [2012] in Figure 8-11. In this study, the complicated and sinuous forms shown in Figure 8-11 are simplified to representative building types similar to those shown in Figure 8-10. The approximate cluster layouts from the work of Zhang et al. [2012] are maintained. Rather than focusing on solar effects, the purpose of this case study is to determine how various building cluster geometries affect the non-dimensional steady state concentration at pedestrian height.

As shown in Figure 8-12, the clusters geometries under consideration are repeated in a 2 x 2 layout. The clusters may be repeated in translation or may be rotated or reflected to form the 2 x 2 layout. This layout is inspired by typical neighborhoods in Singapore. Each corner of the cluster geometry is numbered so that the layout may be
Figure 8-10: Generic building layouts using building geometries representative of those found in Singapore (Adapted from: Leung [2011])

Figure 8-11: Simplified building clusters based on the new towns in Singapore [Zhang et al., 2012]

represented by a 4 x 4 grid of numbers, as shown in Figure 8-12. Within each cluster, the building heights are uniform. This follows the work of Zhang et al. [2012]; they note that in these cases the building heights are approximately uniform because they are near the airport and must be below a certain maximum height. For the work in this section, the cluster geometry is limited to a 190 m x 190 m square area, and the layout is surrounded by 10 m-wide streets with a constant source in the lowest 1 m grid cell, resulting in a 400 m x 400 m domain. The resulting domains were meshed and simulated as described in Section 3.1, with a few exceptions. First, the finest mesh volume was increased by a factor of two in each direction to 1 m x 1 m x 1 m to reduce simulation times for these large domains. Additionally, when the cluster
Figure 8-12: Schematic describing representation of cluster domains

geometry is not aligned with a Cartesian grid, as in Figure 8-12, a pave mesh was used, resulting in hexahedral elements which grow vertically as described in Section 3.1. In plan view these elements remain square and aligned with the Cartesian grid of the domain, however near the buildings the grid transitions (using four-sided elements) to a rotated Cartesian grid to match the orientation of the buildings.

The cluster geometry shown in Figure 8-12 is formally defined for eight “Slabs” domains in Figure 8-13. These are simplified versions of the layout shown in Figure 8-11(b) using the building geometries similar to the Slab Blocks from Figure 8-10. The Slab Blocks were inspired by the forms from the first generation of building cluster types shown in Figure 8-9. This is the oldest building type studied by Leung [2011], placed in a modern layout from the new towns.

Next, two “Courtyard” cluster geometries are displayed in Figure 8-14. These are inspired by the layout shown in 8-11(a) using a building geometry similar to the Courtyards in Figure 8-10. The Courtyards are a simplified version of the building geometries shown in the second and third generation clusters in Figure 8-9. This is second oldest building type studied by Leung [2011], placed in a new town layout.

Two “Grid” cluster layouts are presented in Figure 8-15. These geometries are simplified versions of the cluster layout shown in Figure 8-11(d). The building geome-
1. Slabs: 0 deg

2. Slabs: 90 deg

3. Slabs: Corner parks

4. Slabs: Center parks

5. Slabs: 180 deg

6. Slabs: Dense center

7. Slabs: Edge parks

8. Slabs: 270 deg

Figure 8-13: Cluster geometry: Slabs, 8 resulting domains
tries were simplified to geometries similar to the point towers for high site coverage, shown in Figure 8-10. These point towers are a simplified version of the building geometries shown in the fifth generation of Singapore cluster layouts from Figure 8-9.

Finally, three “Tower” layouts are shown in Figure 8-16. These layouts are based on Figure 8-11(c), however the building geometries have been simplified to geometries similar to the point towers for high site coverage in Figure 8-10.

Each of these cluster geometries has been carefully scaled to cover 24% of the resulting domain plot area, which is in the range of typical values in Singapore. The building plan area to plot area is shown for the five generations of building clusters from Figure 8-9 in Figure 8-17 [Leung, 2011].

These domains were simulated for buildings with a height of 40 m, which results in a ratio of built volume to land area of 9.6 m. This is similar to the gridded neighborhoods presented in Chapter 7, which have a ratio of built volume to land.
area ratio of approximately 8.9 m. Cases with 60 m-tall buildings were also simulated for each of the 15 cluster domains, which is typical for recent construction in Singapore (15-18 stories) [Zhang et al., 2012].

Figure 8-18 shows the non-dimensional steady state concentration averaged over pedestrian height \((z = 0-2 \text{ m})\) in the zone defined as “Areas for pedestrians” in Figure 8-12 for the cases where building heights were set to 40 m. In general the Grid clusters have the lowest non-dimensional concentrations in the pedestrian areas at pedestrian height, while the Courtyard clusters have the greatest non-dimensional concentrations. The Courtyard and Grid layouts are similar to the second generation and fourth generation of building clusters in Singapore, so there may be an improvement in how the building layouts remove scalars in newer generations. The towers are most similar to the 5th generation clusters in Singapore, and these perform relatively well compared to the other types.
Because the $H = 40$ m case has a similar built volume to land area ratio to the gridded neighborhoods presented in Chapter 7, it is possible to compare the magnitude of the concentrations between these two cases with just a few scaling factors.

![Site coverage of representative HDB housing vs. building cluster generation](image-url)
assumptions. Assuming the built volume to land area ratios were exactly equal, it would be fair to compare the concentrations so long as the mass release rate of scalar into a unit plan area were equal for both cases. This can be quantified for each of the cases with the following equation:

\[ m_A = \frac{S V_s}{A}, \]  

(8.1)

where \( m_A \) is the rate of scalar mass released per unit land area \([\text{kg}/(\text{m}^2\cdot\text{s})]\), \( S \) is the release rate of the scalar volumetric source, \( V_s \) is the volume of the source release and \( A \) is the plot area being considered. For the height variation cases, \( m_A = 5.00 \cdot 10^{-5} \text{ kg}/(\text{m}^2\cdot\text{s}) \), while for the clusters, \( m_A = 4.88 \cdot 10^{-5} \text{ kg}/(\text{m}^2\cdot\text{s}) \). Because the mass
release rate per unit land area is approximately equal for these cases the magnitudes of the concentrations at pedestrian height may be compared. The average steady state concentration in the pedestrian areas in the clusters cases is $7.71 \cdot 10^{-4}$ kg/m$^3$. The range of steady state concentrations at pedestrian height for the height variation cases averaged over a particular value of $\sigma_H/\bar{H}$, shown non-dimensionally in Figure B-11, is $2.63 \cdot 10^{-3} - 5.02 \cdot 10^{-3}$ kg/m$^3$. The average cluster case has 3.4 times lower concentration in the pedestrian areas on average compared to the height variation case with the lowest average concentration for a particular value of $\sigma_H/\bar{H}$. This may be due to the increased ratio of open area to total area for the clusters cases which would allow the same mass of scalars in a pedestrian height zone, if spread evenly, to result in lower overall concentrations. The plot area to open area ratio for the clustered geometries is only 1.9 times greater than that of the height variation cases, therefore this cannot explain all of the difference in the concentrations. The difference in concentrations may also be due to the source location. In the clusters cases the source location may be more advantageous because high concentrations in the street zones are not counted towards the pedestrian height concentrations. This advantage may not be present if the wind direction changes slightly to an angle that is not aligned with one of the streets. Finally, clustered building geometries may simply be better at removing scalars from the pedestrian areas. The results for the $H = 60$ m case are shown in Appendix B.6 in Figure B-13. These preliminary results show that increasing the building height (and therefore the built volume per unit land area) seems to have little effect on the dimensionless steady state concentrations in the pedestrian areas. An urban designer must consider, however, that in higher density areas the source magnitudes may be larger, resulting in larger overall concentration magnitudes.

Though the work in this section is not comprehensive, it suggests that clusters are promising as an urban typology that may produce lower concentrations in urban areas at pedestrian height. These geometries should be explored further in a more systematic way using the physics-based approach developed in this thesis.
Chapter 9

Practitioner supplement

This chapter summarizes the results from this thesis that are relevant to practitioners such as urban designers and policy makers in plain terms. Additionally, relevant extensions of the results are presented and the urban design implications are discussed. This chapter stands alone as a supplement to the thesis and may be used independently.

Many of the anthropogenic sources that affect the temperature and pollution levels in a particular neighborhood are released near the ground. These sources include emissions from cars, trucks and buses, anthropogenic heat from pedestrians, heat and pollutants from building and road construction and sometimes waste heat from buildings. These scalars maybe advected horizontally to another part of the neighborhood, however in a large neighborhood one may assume that if there is enough wind to advect scalars away from one area, there will also be enough wind to advect scalars from elsewhere to that same area. Therefore, in large urban areas one should design built form to remove these scalars vertically, from the area below the building heights, known as the urban canopy layer (UCL), to the volume above the building heights, known as the urban boundary layer (UBL).

Consider a gridded, repetitive neighborhood of constant height, shown schematically in Figure 9-1. Dimensional reasoning shows that for this geometry with a near-ground source release, shown in Figure 9-1 as $H_s = 0.5$ m, the steady state
dimensionless concentration averaged over the volume below roof level is a function of the following variables:

\[
\frac{C_{ss} u_a}{S H_s} = f \left( C_f, \frac{L}{L_{int}}, \frac{W}{W_{int}}, \frac{H}{L_{int}}, \frac{W_{int}}{L_{int}} \right), \tag{9.1}
\]

where \( C_{ss} \) is the average steady state concentration of the scalar over the volume of interest, \( S \) is the release rate, \( u_a \) is the wind speed, \( C_f \) is the skin friction coefficient of the surfaces in the domain, and \( L, W, H, W_{int} \) and \( L_{int} \) are the length scales defined in Figure 9-1. The derivation of Equation 9.1 is presented in Chapter 4.

When \( H/L_{int} = 2 \) and \( W_{int}/L_{int} = 1 \), the other geometric parameters may be independently varied to understand the effect of changing the building lengths and widths on the vertical mixing potential of the neighborhoods. The dimensionless concentrations averaged over pedestrian height, from \( z = 0 \) to \( z = 2 \) m, are presented in Figure 9-2. Details of the techniques used to calculate these results are presented in Chapter 3. The numbered contours represent curves of constant \( \beta \), defined as:

\[
\beta = \frac{L W H}{(L + L_{int})(W + W_{int})}. \tag{9.2}
\]
Figure 9-2: Contours of \((C_{ss} u_a) / (S H_s)\) for \(W\) [m] vs. \(L\) [m] at steady state, averaged over pedestrian height within the UCL, from \(z = 0 - 2\) m with contours of constant \(\beta\)

\(\beta\) is the fraction of built volume to plot area, a measure of capacity for a particular neighborhood. If the desired capacity is known for a neighborhood in the design phase, Figure 9-2 could be used to evaluate designs in the context of vertical mixing potential or could help the designer best meet the selected value of \(\beta\). For example, if an urban planner’s goal is to have \(\beta \geq 15\) m and the initial design uses \(L = 112\) m and \(W = 48\) m, Figure 9-2 may lead the planner to decrease \(L\) and increase \(W\) by moving to the left along the curve of \(\beta = 15\) m. The planner may also notice that increasing \(W\) while maintaining \(L = 112\) m will also result in reduced average concentrations at pedestrian height while increasing capacity of the urban area which may be advantageous for other reasons. It is important to note that Figure 9-2 is true for any value of \(S\), however increasing \(\beta\) may lead to a larger \(S\) due to a larger population living and driving within the neighborhood. \(S\) scales directly with \(C_{ss}\), as shown in Equation 9.1, therefore it is important to anticipate \(S\) to understand
the magnitude of the undesirable scalar sources which may be present in a particular urban area.

Urban designers, architects and business owners may be interested to know more detailed information about the concentrations within the neighborhood. To this end, the results in Figure 9-2 may also be presented at street canyon scale. Three different volumes are defined within a gridded neighborhood in Figure 9-3: long canyons, cross canyons and intersections. In the case in Figure 9-2, the volumes of the long canyons,

\[(L \cdot W_{int} \cdot H)\]

are varied because \(L\) varies from 16 – 144 m. Similarly, the volumes of the cross canyons, \((W \cdot L_{int} \cdot H)\), are varied because \(W\) varies from 16 – 144 m. The volumes of the intersections, \((L_{int} \cdot W_{int} \cdot H)\), are not varied because each of those parameters is constant.

The dimensionless steady state concentration at pedestrian height is presented for the long canyons in Figure 9-4. These values are consistently higher than the neighborhood scale dimensionless concentrations at pedestrian height. The same results are presented for the cross canyons in Figure 9-5. The surface is presented using the same color bar scale as the long canyon case so that they may be compared more easily. Not only are the concentrations in the cross canyons more than a factor of two lower than those in the long canyons for a particular neighborhood at pedestrian
height, but the cross canyons concentrations are also lower than the neighborhood scale concentrations in Figure 9-2 for a particular neighborhood. Though there are variations in both the long and the cross canyon data as $L$ and $W$ are varied, these may be considered secondary to the large differences in the concentrations between the two volume types. For the interested reader, these small variations and the physics causing them are discussed at length in Chapter 5. The large differences in concentrations between the long canyons and the cross canyons suggest that it is preferable to have a gridded neighborhood with slabs oriented perpendicular to the predominant wind direction to reduce concentrations in a neighborhood, on average. This may not always be possible due to other design constraints, however a designer may still make use of this outcome. For example, if a building takes up an entire city block and the HVAC intakes must be located on one of the four building façades, it
would be prudent to place the intakes in a cross canyon over a long canyon because the air is likely to have lower pollution levels. Similar arguments could be made to an architect for locating operable windows in a large office building. Additionally, placing services where pedestrians will spend any length of time outside, such as a coffee shop or restaurant with outdoor seating, should also be located in cross canyons to reduce pedestrian exposure to pollutants. More detailed examples making using of the flow fields at intersections are presented in Chapter 5. The intersection results are shown for this setup in Figure 9-6. Because the intersection volumes are small in comparison to the other volumes in most cases, one may categorize them as part of the long canyons or part of the cross canyons according to the results in Figure 9-6.

The intersections transition from behaving like cross canyons for small values of $L$ to

Figure 9-5: Contours of $(C_{ss} u_a) / (S H_s)$ for $W$ [m] vs. $L$ [m] at steady state, averaged over pedestrian height within the cross canyons, from $z = 0$–2 m with contours of constant $\beta$
behaving more like long canyons for larger values of $L$. The results are not sensitive to values of $W$. This outcome is explained in Chapter 5.

Figure 9-6: Contours of $(C_{ss} u_a) / (S H_a)$ for $W$ [m] vs. $L$ [m] at steady state, averaged over pedestrian height within the intersections, from $z = 0$ - 2 m with contours of constant $\beta$

These results, for the $H/L_{int} = 2$ and $W_{int}/L_{int} = 1$ cases, provide insight into the differences between cross canyons and long canyons and are useful for understanding and quantifying the physical phenomena that make gridded neighborhoods different than infinite canyons. These phenomena include increases in mean vertical and turbulent exchanges as well as the presence of lateral exchanges at the interfaces of the various UCL volumes, and are explained in Chapter 5. These results are limited, however, in that they do not address what happens when the final two geometric parameters in Equation 9.1, $H/L_{int}$ and $W_{int}/L_{int}$ are varied. To address this, Equation
9.1 is rewritten as:

\[
\frac{C_{ss} u_a}{S H_s} = f \left( C_f, \frac{L}{H}, \frac{W}{H}, \frac{L_{int}}{H}, \frac{W_{int}}{H} \right). \tag{9.3}
\]

This rearrangement of the non-dimensional geometric parameters is possible so long as the dimensionless groups remain independent. Further, Equation 9.3 is rearranged to:

\[
\frac{C_{ss} u_a}{S H_s} = f \left( C_f, \frac{L}{H}, \frac{W}{H}, \frac{H}{L_{int}}, \frac{H}{W_{int}} \right). \tag{9.4}
\]

This form of the dimensionless geometric parameters is useful because the latter two terms represent the aspect ratios of the cross canyons and long canyons, respectively, which is a common way to describe the geometry of a street canyon. Additionally, the form of the geometric parameters in Equation 9.4 is intuitive, meaning one should be able to picture how the geometry in a gridded area would change as each of the four parameters is varied.

Using three-dimensional surface plots, variation in more of the geometric parameters in Equation 9.4 may be visualized. The following surface plots were created using the assumptions discussed in Chapter 6. Most notably, the plots are based on infinite canyon results. This assumption is premised on the concept that as the street canyons get longer they behave more like infinite canyons. Additionally, the intersection concentrations are ignored because the average neighborhood concentration is a weighted average of the concentrations in the three volumes and the intersection volume is an increasingly small portion of these neighborhoods as the street canyons get longer. Additional assumptions and further discussion of these assumptions are presented in Chapter 6.

Figure 9-7 shows dimensionless concentrations for \( W/H = 4 - 20 \), \( L/H = 4 - 20 \) and \( H/L_{int} = H/W_{int} = 2 - 8 \). Setting the two final parameters equal to each other as they are varied equates this variation in four parameters to variation in three independent parameters. The dimensionless concentrations are averaged over the entire neighborhood volume, from the ground to the top of the buildings. The increases in \( W/H \) and \( L/H \) from 4 - 20 are equivalent to making the cross canyons
and the long canyons longer, respectively. The increase $H/L_{int} = H/W_{int}$ from 2 - 8 could be imagined as increasing the building height for a particular layout, with all other geometric parameters held constant. Each surface in Figure 9-7 represents a particular value of $H/L_{int} = H/W_{int}$. It is apparent from this graphic that variations in $H/L_{int} = H/W_{int}$ have a large effect on the neighborhood scale concentrations. This is more easily seen by projecting these surfaces on the $L/H, (C_{ss} u_a)/(S H_s)$-plane, shown in Figure 9-8. The surfaces are colored by the street canyon aspect ratios, $H/L_{int} = H/W_{int}$. As expected from the previous discussion of cross canyons and long canyons, there is an increase in the dimensionless concentration as $L/H$ increases. This is consistent with the result that long canyons have higher concentrations than cross canyons, and in cases with large values of $L/H$ an increasingly larger portion of the neighborhood will be made up of long canyons for a given value of $W/H$. This rise in concentration is practically negligible in comparison to the increase in

Figure 9-7: Surfaces of $(C_{ss} u_a)/(S H_s)$ for $W/H$ vs. $L/H$ for various values of $H/L_{int} = H/W_{int}$
Figure 9-8: Surfaces of $(C_{ss\, u_a})/(S\, H_s)$ for $W/H$ vs. $L/H$ projected onto the $L/H, (C_{ss\, u_a})/(S\, H_s)$-plane for various values of $H/L_{int} = H/W_{int}$

dimensionless concentration with increasing values of $H/L_{int} = H/W_{int}$. Though the contours of constant $\beta$ are not projected onto these surfaces, it is apparent that when designing a gridded urban area with $H/L_{int} = H/W_{int}$ one should choose the lowest possible value of $H/L_{int} = H/W_{int}$ that meets the $\beta$ requirements and other design constraints. There is little maneuvering in the values of $L/H$ or $W/H$ that could improve the concentration levels as much as reducing $H/L_{int} = H/W_{int}$ by one, especially for $H/L_{int} = H/W_{int} > 3$. Similarly, the surfaces in Figure 9-7 are projected onto the $W/H, (C_{ss\, u_a})/(S\, H_s)$-plane in Figure 9-9. As expected, there is a decrease in dimensionless concentration for increasing values of $W/H$ because this is equivalent to increasing the fraction of the neighborhood that made up of cross canyons. This decrease, however, is small in comparison to the decrease seen when decreasing $H/L_{int} = H/W_{int}$ by one. This further confirms the importance of reducing $H/L_{int} = H/W_{int}$ as much as possible in the design of a gridded neighborhood.
Using the infinite canyon results in Chapter 6, a surface could be generated for
\( \frac{W}{H} = 4 - 20, \frac{L}{H} = 4 - 20 \) and any value of \( \frac{H}{L_{\text{int}}} \) between two and eight with a
distinct value for \( \frac{H}{W_{\text{int}}} \) between two and eight. An interesting example for designers
and policy makers would be fixing \( \frac{H}{L_{\text{int}}} = 2 \) while varying \( \frac{H}{W_{\text{int}}} \). This is equiv­
alent to varying the aspect ratio of the long canyons while keeping the cross canyon
aspect ratios constant for each neighborhood. The cross canyons are set to the low­
est aspect ratio studied, making them the widest canyons considered relative to the
building height. This could be considered an “avenue,” which may have extra space
in the street for architectural elements such as a center island or additional street
parking. The long canyons become increasingly narrow as \( \frac{H}{W_{\text{int}}} \) increases, and will
be considered “streets” in this context. The six surfaces for each value of \( \frac{H}{W_{\text{int}}} \) are
displayed in Figure 9-10 with the same color bar scale as Figure 9-7 for comparison.
In general, the addition of an “avenue” has reduced the overall neighborhood scale
concentrations for a particular value of \( \frac{H}{W_{\text{int}}} \) when comparing the surfaces in Figure
9-10 to those in Figure 9-7. There is also a reduction in concentration with increasing \(W/H\) and decreasing \(L/H\) for a given \(H/W_{int}\). These reductions are greater than those seen in the \(H/L_{int} = H/W_{int}\) cases for variations in \(W/H\) and \(L/H\). Additionally, the difference in concentrations between the maximum and the minimum values on a particular surface is increasingly large for increasing values of \(H/W_{int}\). These trends are easier to see when projected onto the \(L/H,(C_{ss} u_a)/(S H_s)\)-plane, shown in Figure 9-11. Though the extents of the surface for the \(H/W_{int} = 8\) cases, for example, are hidden behind the other surfaces, it is apparent that reducing \(L/H\) could be as effective at reducing neighborhood scale concentration as reducing \(H/W_{int}\) by one. The results from Figure 9-10 are projected onto the \(W/H,(C_{ss} u_a)/(S H_s)\)-plane in Figure 9-12. As in Figure 9-11, parts of some of the surfaces are hidden from view behind other surfaces, however it is apparent that increasing \(W/H\) could be a more effective way to reduce neighborhood scale concentration in these cross canyon...
Figure 9-11: Surfaces of \((C_{ss \, u_a})/(S \, H_s)\) for \(W/H\) vs. \(L/H\) projected onto the \(L/H, (C_{ss \, u_a})/(S \, H_s)\)-plane for various values of \(H/W_{int}, \ H/L_{int}=2\)

 IPCC “avenues” cases than in the \(H/L_{int}=H/W_{int}\) cases. Considering contours of equal \(\beta\) across multiple surfaces of constant \(H/W_{int}\) is worthwhile when trying to improve the preliminary design of a gridded neighborhood aligned with the wind with cross canyon “avenues.” This is left as an exercise for the reader.

Another interesting example for urban designers and policy makers would be the introduction of long canyon “avenues,” where \(H/L_{int}\) is varied from two to eight and \(H/W_{int}=2\). These results are shown for \(W/H=4-20\) and \(L/H=4-20\) in Figure 9-13. In general, these concentrations are lower for a given value of \(H/L_{int}\) in comparison to the \(H/L_{int}=H/W_{int}\) cases. Additionally, these cases may be directly compared to the cross canyon “avenue” cases because the ranges of \(\beta\) are the same for the surfaces of a particular “street” aspect ratio. The maximum concentrations for a particular surface are lower for the long canyon “avenue” cases, however these maxima occur at different values of \(W/H\) and \(L/H\). In the case of long canyon “avenues,” concentrations for large values of \(H/L_{int}\) are lowest for large
values of $L/H$ and small values of $W/H$. This would be considered slab architecture aligned with the wind. The minimum case for $H/L_{int} = 8$ is when $W/H = 4$ and $L/H = 20$, and this has the same $\beta$ as the minimum case for cross canyon "avenues" with $W/H = 20$, $L/H = 4$ and $H/W_{int} = 8$. The concentrations in these cases are comparable. In the maximum cases for these two surfaces, however, though the value of $\beta$ is equal, the long canyon "avenue" case has a lower concentration than the cross canyon "avenue" case, which is an outcome that is directly applicable to urban planning and policy making for a neighborhood with a gridded layout of "avenues" orthogonal to streets with a dominant wind direction. The surfaces in Figure 9-13 are shown projected onto the $L/H,(C_{ss} u_a)/(S H_s)$-plane in Figure 9-14. This view shows that the concentrations are lower in general in comparison to the cross canyon "avenue" cases. Because long canyons have greater concentrations in general, it makes sense that reducing their aspect ratios to the minimum value considered would be more effective at reducing neighborhood scale concentrations.
than reducing the aspect ratios of cross canyons to the minimum value considered. For $H/L_{int} = 2 - 5$, the concentration is relatively insensitive to changes in $W/H$ and $L/H$, therefore capacity or $\beta$ can be varied by varying $L/H$ or $W/H$ for a particular value of $H/L_{int} = 2 - 5$ with almost no consequence for the vertical exchange between the UCL and the UBL. For the $H/L_{int} = 6 - 8$ cases, it would be worthwhile to plot the contours of constant $\beta$ on each surface before determining if varying $L/H$ or $H/L_{int}$ is the best solution for reducing the concentration or increasing $\beta$. Figure 9-15 shows the surfaces in Figure 9-13 projected onto the $W/H,(C_{ss}u_a)/(S H_s)$-plane. Similar to the previous figure, one would need to plot the contours of constant $\beta$ for the $H/L_{int} = 6 - 8$ cases to determine the prudence of varying $W/H$ or $H/L_{int}$ as a means to reduce concentrations or increase $\beta$.

Transient considerations, meaning how quickly the concentrations get to steady state, could be relevant to urban design in the cases with large time constants. The
implications of long time constants are touched upon in Chapter 5 and are discussed in Chapter 6 in detail.

Beyond variations of the geometric variables in Equation 9.4, the vertical exchange between the UCL and the UBL may be enhanced through the introduction of variation in building heights or through the introduction of parks and open areas, discussed in some detail in Chapters 7 and 8, respectively. In general, designing some building height variation in a gridded neighborhood will reduce the neighborhood averaged concentration. Height variation also increases exchange between the cross canyons and the long canyons resulting in a more well-mixed neighborhood, meaning the large discrepancies between the long canyons and the cross canyons shown for the $H/L_{int} = 2$ and $W_{int}/L_{int} = 1$ cases in Figures 9-4 and 9-5 becomes almost negligible, on average. A single street canyon, however, in a neighborhood with height variation may have a concentration which is much higher than expected for the same type of canyon in a neighborhood without height variation. Therefore, when designing a
Figure 9-15: Surfaces of \((C_{ss} u_a)/(S H_s)\) for \(W/H\) vs. \(L/H\) projected onto the \(W/H,(C_{ss} u_a)/(S H_s)\)-plane for various values of \(H/L_{int}, H/W_{int} = 2\).

particularly high pedestrian traffic attraction in neighborhoods with height variation, further analysis should be performed to ensure that the attraction is not placed in a high concentration volume. To a lesser extent than height variation, parks and open areas result in lower neighborhood averaged concentrations as well as somewhat more well-mixed neighborhoods. One must carefully consider if replacing buildings with open areas will result in the need to make the remaining buildings taller, because this will result in higher overall concentrations as shown in Figure 9-7.

Another approach to consider, which was addressed briefly as a case study in Chapter 8 is using clustered building geometries to form neighborhoods rather than a gridded layout. These clusters have lower site coverage ratios for a particular value of \(\beta\), and preliminary results show that they may be advantageous for designing for reduced concentrations at pedestrian height.
9.1 Limitations

The work in this thesis is meant to be applied to dense urban areas. It should not be applied to cases with street canyon aspect ratios lower than two. These cases have fundamentally different flow fields than the dense cases, which are in the skimming flow regime [Oke, 1987]. Additionally, the work in this thesis ignores buoyant forces when calculating the motion of the scalars through the UCL. Therefore, this work is limited to the scenario where the flow in the UCL is driven by a prevailing wind above, rather than buoyant flows due to façades and street surfaces which have been heated by the sun or anthropogenic sources. Cutoffs for this assumption are presented in Hall [2010]. Another limitation is that the orientation of the flow is kept aligned with one of the grid axes. Future work includes gaining insight to the flow phenomena and quantifying results for the cases where the gridded neighborhoods are not aligned with the wind. Finally, this work does not account for the additional sources of turbulence which are prevalent in urban areas. These include the motion of pedestrians, vehicles and large “roughnesses” found in street canyons such as trees and awnings.

Despite these limitations, the work in this thesis meets the three goals outlined in Chapter 3, and restated here:

- To quantitatively compare the vertical mixing potential of common urban forms as their geometries are parametrically varied by assessing their steady state concentrations at both street canyon and neighborhood scales
- To gain insight into the flow phenomena responsible for these quantitative results using fluid mechanics and grid-scale simulation data
- To summarize these results at both street canyon and neighborhood scales so they may be used by urban designers and policy makers to inform early phase planning and zoning policy
Chapter 10

Conclusions

This thesis aims to quantify the vertical mixing potential of urban forms and gain insight into the physics responsible for these findings. This is achieved with the use of computational fluid dynamics and fluid mechanical reasoning. Results are presented at both a street canyon and a neighborhood scale, and the implications of these results are discussed in the context of urban design. An accessible, supplemental summary of the most relevant results to practitioners is developed. This makes it possible for this work to be applied by practitioners to influence policy and design decisions in rapidly growing urban areas.

Orthogonally-gridded neighborhoods with uniform building heights and one grid axis aligned with the wind were studied comprehensively in this research. Street canyons perpendicular to the wind were found to have greater vertical mixing potential than those aligned with the wind. For a street canyon aspect ratio of two, over the range of building lengths studied, the average concentrations at pedestrian height in the street canyons aligned with the wind were about three times greater than those perpendicular to the wind for cases with a constant near-ground volumetric source release. For new urban areas this result may lead practitioners to design more slab-like neighborhoods with the slabs aligned perpendicular to the dominant wind direction. Additionally, services with large amounts of pedestrian traffic, operable windows and HVAC intakes could be preferentially placed in street canyons
perpendicular to the dominant wind direction to avoid human exposure to high concentration levels. In the cases where the street canyon aspect ratio was equal to two, a three-dimensional vortex was discovered near the interface of the street canyons perpendicular to the wind and the intersections. This vortex leads to near-ground mean flows from the canyons perpendicular to the wind to the downwind canyons aligned with the wind. This result may guide practitioners to avoid placing frequent transient emission sources due to such services as bus stops or truck loading areas near this three-dimensional vortex. This is because the associated emissions will lead to increased concentrations in the street canyons aligned with the wind, which have a lower mixing potential. Increasing street canyon aspect ratios by one was found to decrease vertical mixing potential significantly. For the range of street canyon aspect ratios considered, most neighborhood-averaged concentrations were reduced 25-50% when the aspect ratio in the entire neighborhood was reduced by unity. This outcome could guide policy makers in selecting maximum street canyon aspect ratios in a new development or in the redevelopment of existing urban areas.

Additional urban planning elements were assessed as a means to further improve vertical mixing potential beyond those possible with a gridded neighborhood of uniform height aligned with the wind. Varying the normalized standard deviation of building heights from the average building height increased the vertical mixing potential at a neighborhood scale due to enhanced vertical mean flows. For an average street canyon aspect ratio of two and for the building lengths and widths considered, the neighborhood-averaged concentrations at pedestrian height were reduced by about 25% in comparison to the uniform height case with just a minimal amount of height variation from average, \( \sigma_H/H = 0.07 \). Additionally, variation in building heights led to increases in lateral mean flows among the various street canyons leading to more well-mixed neighborhoods. Urban designers could vary building heights as a means to drastically improve the low vertical mixing potential of street canyons aligned with the wind. Policy makers may also be interested in setting a minimum level of height variation for new urban areas to improve the vertical mixing potential at a neighborhood scale. Introducing parks and open areas to orthogonally gridded
neighborhoods was also found to improve vertical mixing potential at a neighborhood scale, specifically in street canyons aligned with the wind. Finally, preliminary work on tall clustered buildings with large open areas show that this typology could have much greater vertical mixing potentials than gridded neighborhoods in general.

The quantitative results in this thesis are only applicable in dense urban areas surrounded by similarly dense urban areas. The outputs of this work should not be used for cases where buoyant forces drive the flow field in the UCL; they are meant for the condition where the flow in the UCL is driven by the wind in the UBL. To determine if buoyant flows are dominant in comparison to forced flows, one may calculate the Richardson number for a particular street canyon or street canyon surface [Hall, 2010]. The findings should only be applied to geometries similar to the cases presented, primarily orthogonally gridded neighborhoods aligned with the wind.

Though this thesis does not cover all of the relevant urban geometries likely to be present in new neighborhood designs, the methodology used herein could be used as a framework for future work in this field. Parametric studies supported by a robust understanding of the trends in the results allows the work to be interpolated and extrapolated with confidence. Additionally results obtained in this manner may be extended to distinct but similar geometries so long as the user fully understands the physics behinds the results and deems them applicable to the new geometries. Outcomes using this approach are far more compelling than parametric studies with no explanation of the results.

In the future, the work could be extended to include additional parameters to vary in a gridded neighborhoods such as the orientation of neighborhoods relative to the freestream flow field. Combining results at different orientations with the wind rose for a development site, a practitioner could optimize the orientation of a gridded neighborhood for maximum vertical mixing potential. This research includes the zero and ninety degree cases for many geometries, therefore it may be possible to understand the physics of the flow fields when changing the grid orientation with only two or three additional simulations per case.
Finally, a comprehensive study of clustered building layouts is a worthwhile future pursuit because preliminary results in this thesis suggest these geometries may have greater vertical mixing potentials than gridded neighborhoods.
Appendix A

Turbulence model selection

As discussed in Section 2.2.3, RANS simulations are less computationally expensive than LES simulations, making them useful for applications where the flow field is only being simulated to compute the value of a few quantitative outputs. They are accurate enough to capture the mean flow structures around urban forms when compared with wind tunnel results, and are frequently used to simulate neighborhood-scale urban geometries [e.g. Hang and Li [2010] and Hang et al. [2011]].

These models tend to overestimate turbulence near separation zones which are common in simulations with bluff body flow near the windward entry [Hang et al., 2011]. They qualitatively capture the turbulent kinetic energy trends in many cases, however the exact magnitude of turbulent kinetic energy should not be assumed correct [Hang et al., 2011]. A RANS turbulence model is used in this thesis, and the regions of separation near the windward entries are avoided in many cases by using periodic boundary conditions at the inlet and outlet to approximate fully developed flow (discussed in Section 3.1).

Li et al. [2005] compared the air changes per hour in street canyons with aspect ratios of 0.5, 1.0 and 2.0 using LES and $k$-$\epsilon$ models. They found that the air change rates were overpredicted with the $k$-$\epsilon$ model, but all of the values were within 20% of the LES results. This same data was compared to water tunnel results in Li et al. [2008a] and they found that the flow field in the case with a street canyon aspect
ratio of 0.5 was not as well predicted with the \( k-\epsilon \) model because this case is in the wake interference regime, rather than the skimming flow regime. Both models well predicted the experimentally measured velocities in the larger aspect ratio cases which are in the skimming flow regime. The geometry for the case with a street canyon aspect ratio of 1.0 is shown schematically in Figure A-1 (a). The LES, \( k-\epsilon \) and water tunnel results are presented in Figure A-1 (b) with a black solid line, a black dashed line and gray squares, respectively. The left side of Figure A-1 (b) shows the normalized mean horizontal velocity at \( x/b = 0.25 \), depicted with a gray dashed line in Figure A-1 (a). The normalized vertical velocity taken along the same line is shown on the right side of Figure A-1 (b). Additional results were computed with the \( k-\epsilon \) model in the ANSYS Fluent software used in this thesis. These results are shown as the green, blue and red lines in Figure A-1 (b). The cases with green lines and blue lines were run with QUICK as the spatial discretization scheme for momentum, turbulent kinetic energy and turbulent dissipation rate. The results shown with red lines were run with the third-order MUSCL spatial discretization scheme for momentum, turbulent kinetic energy and turbulent dissipation rate. These schemes blend the second order upwind scheme with other schemes to make them higher order. The results shown with the blue lines and red lines were initialized with full multi-grid initialization to accelerate the solutions. The pressure-velocity coupling scheme was set to SIMPLEC and pseudo transient was turned off for these three cases. Aside from these changes, the setups were the same as those used in this thesis. The mean flow results from these three simulations are similar to the LES and water tunnel results. Additionally, these three match the LES and water tunnel results better than the \( k-\epsilon \) model from Li et al. [2005] for vertical velocity, as shown on the right side of Figure A-1 (b).

All of the simulations in this thesis calculating flows around orthogonally gridded neighborhoods with buildings of constant height are in the skimming flow regime, which is the regime where Li et al. [2008a] found that \( k-\epsilon \) models provide similar results to LES models. Even in the wake interference regime, the air changes per hour were within 20% of LES results using \( k-\epsilon \). Based on the number of simulations nec-
ecessary to meet the goals of this thesis, and considering the known trade-offs between computational time and accuracy, RANS models were deemed to be acceptable for the purposes of meeting the goals of this thesis. In some cases more exact solutions are necessary, for example when maximum wind speeds are a safety concern in an urban area where a new building is about to be constructed. To precisely determine how a new building affects wind speeds and turbulence levels in a particular city when safety is a concern, LES simulations should be considered as an alternative to RANS simulations.
Figure A-1: (a) Schematic of two-dimensional street canyon used to evaluate simulation techniques; (b) Comparison of water tunnel and CFD results for a two-dimensional street canyon [Li et al., 2008a]
Appendix B

B.1 Additional dimensionless concentration data for variations in building length and building width, averaged over UCL volumes

Figure B-1: Contours of $(C_{ss} u_a) / (S H_s)$ for $W$ [m] vs. $L$ [m] at steady state, averaged over long canyons
Figure B-2: Contours of \( \frac{(C_{ss} u_a)}{(S H_s)} \) for \( W \) [m] vs. \( L \) [m] at steady state, averaged over cross canyons.
Figure B-3: Contours of \( \frac{(C_{ss} u_a)}{(S H_s)} \) for \( W \) [m] vs. \( L \) [m] at steady state, averaged over intersections.
B.2 Additional dimensionless concentration data for variations in building length and building width, averaged over pedestrian height

Figure B-4: Contours of \( \frac{(C_{ss} u_a)}{(S H_s)} \) for \( W \) [m] vs. \( L \) [m] at steady state, averaged over long canyons at pedestrian height, from \( z = 0\text{-}2 \) m
Figure B-5: Contours of \((C_{ss} u_a) / (S H_s)\) for \(W \text{ [m]}\) vs. \(L \text{ [m]}\) at steady state, averaged over pedestrian height within the UCL, averaged over cross canyons at pedestrian height, from \(z = 0\) to \(2 \text{ m}\).
Figure B-6: Contours of $(C_{ss \, u_a}) / (S H_a)$ for $W$ [m] vs. $L$ [m] at steady state, averaged over pedestrian height within the UCL, averaged over intersections at pedestrian height, from $z = 0$–2 m.
B.3 Dimensionless concentration data for variations in street canyon aspect ratio, averaged over pedestrian height

Figure B-7: \( \frac{(C_{ss}u_a)}{(S H_s)} \) vs. \( H/L_{int} \) at steady state, averaged over the UCL at pedestrian height, from \( z = 0-2 \) m
Figure B-8: \( \frac{(C_{ss} u_a)}{(S H_s)} \) vs. \( H/L_{int} \) at steady state, averaged over pedestrian height UCL volumes, from \( z = 0 \text{–} 2 \text{ m} \)
B.4 Dimensionless concentration data, adjusted for increased source levels, for variations in street canyon aspect ratio

Figure B-9: \( \frac{(C_{ss2} u_0)}{(S_2 H_s)} \times \frac{(S_i)}{(S_2)} \) vs. \( H/L_{int} \) at steady state, averaged over UCL volumes
Figure B-10: \(\left(\frac{C_{ss2 \, u}}{S_2 H_a}\right) \times \left(\frac{S_i}{S_2}\right)\) vs. \(H/L_{int}\) at steady state, averaged over pedestrian height UCL volumes, from \(z = 0-2\) m.
B.5 Dimensionless concentration data for variations in building height, averaged over pedestrian height

![Graph showing dimensionless concentration data](image-url)

Figure B-11: $\left( \frac{C_{ss} u_a}{S H_s} \right)$ vs. $\frac{\sigma_H}{\bar{H}}$, averaged over pedestrian height UCL volumes of each neighborhood, from $z = 0.2$ m
Figure B-12: \( \frac{(C_{ss} u_a)}{(S H_s)} \) vs. \( \frac{\sigma_H}{\bar{H}} \), averaged over pedestrian height UCL volumes of each neighborhood, from \( z = 0 \text{--} 2 \text{ m} \).
B.6 Dimensionless concentration data for clusters with $H = 60$ m, averaged over pedestrian height

![Bar chart showing concentration data for different clusters.](chart.png)

Figure B-13: $(C_{ssu_a})/(SH_s)$ in “Areas for pedestrians” vs. cluster type for $H = 60$ m buildings, averaged over pedestrian height, from $z = 0\text{-}2$ m
Bibliography


