THE URBAN HEAT ISLAND EFFECT IN DENSELY POPULATED URBAN AREAS AND ITS IMPLICATIONS ON ECO-CITY PLANNING: INVESTIGATION OF VERTICAL TEMPERATURE PROFILES IN DOWNTOWN VANCOUVER

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Abstract

The urban heat island effect at the surface is influenced by the 3D characteristics of the local landscape, including vegetation cover and material types. However, little research exists exploring the effect of urban features on local vertical atmospheric profiles within dense urban areas. This study collected vertical temperature data with Remotely Piloted Aircraft Systems at four sites in downtown Vancouver representing varying levels of urbanization and surface coverage. Data was collected in the morning and afternoon in summer and winter. Temperature profiles were compared against percentage vegetation, tree canopy coverage, percentage impervious surfaces, building heights, and material types. A significant difference was noted between the four sites in summer (up to 4°C), but not in winter. In the summer, warmer air temperatures were found in the morning and afternoon at the most urban site with the highest building density, least vegetation, and most impervious surfaces, up to 120m, but surface temperatures at this site were cooler due to shading. Air above the park site was cooler throughout the day. Two sites located near the ocean did not behave as expected: one had high afternoon air temperatures despite proximity to heat mitigating features, while the other had lower afternoon air temperatures despite low percent vegetation and high imperviousness. Air temperatures at these sites were likely influenced by horizontal advection forces from land-sea breezes. Additional research on vertical temperature profiles in a wider variety of urban areas would be beneficial to better understand the impact of urban features on atmospheric heat.

1.0 Introduction and Background

As the world struggles with climate change and rising temperatures, the effect of urban landscapes on local temperatures is becoming a phenomenon of public concern. The Urban Heat Island (UHI) is defined as the existence of recognizably warmer temperatures within urban areas compared to those in rural areas [1, 2]. Urbanization has a significant effect on the surrounding atmosphere and is a driver of climate change through processes such as land degradation, deforestation, high proportions of heat-retaining materials, and increased per capita emissions of greenhouse gases [3]. Heat waves are often more intense within cities, and are correlated with adverse health impacts such as increased mortality among vulnerable populations such as the chronically ill, elderly, and young children [3, 4]. Heat also plays a key role in the chemistry of air pollution and photochemical smog formation [4,5,1]. At present, population distributions are shifting towards cities, and it is expected that 70% of the global population will live in cities by 2050 [3]. With so much of the population dwelling in urban regions, it is more important than ever for municipalities to adapt to rising temperatures with heat mitigating urban design strategies.

Vancouver has typically enjoyed a mild and temperate climate, and its urban design policy has historically focused on features that take advantage of periods of sunlight or on protection from rain [5]. Because of this historically temperate climate and resulting design policy, Vancouver may be more vulnerable to the negative impacts of increasing temperatures. The frequency of Vancouver's annual heat days – where the temperature exceeds 30°C – is expected to rise from two days up to 14 days annually by 2050[6]. Vancouver is thus a prime candidate for UHI research, with resulting knowledge allowing Vancouver to shift its urban design policy towards addressing rising temperatures.

With the aforementioned issues in mind, a detailed understanding of the urban atmosphere and its influence on the UHI is needed. Previous research on the UHI has been extensive, but investigations into the impact of the three-dimensional urban landscape on heat creation are more recent. Research specifically into the vertical structure of urban heat islands is limited, however. Remotely Piloted Aircraft Systems (RPAS, AKA drones) provide a simple, cost effective, and accessible way to measure the vertical characteristics of the urban atmosphere.

This research paper investigates whether urban characteristics and morphological features have an impact on the vertical temperature structure of the UHI within the dense urban landscape of downtown Vancouver. The objectives of this study are (1) to measure, analyze, and compare the vertical temperature profiles of four sites around downtown

Vancouver with RPAS; (2) to assess whether the morphological features and characteristics of each site have any impact on the vertical temperature profiles; (3) to consider temperature profiles at each site in two separate seasons to assess seasonal variation; and (4) to consider the data and discuss results within the context of eco-city strategies, and apply the information gained to the City's and the Region's future heat mitigation strategies. Specifically, the City of Vancouver's Greenest City Action Plan [7], Vancouver's Urban Forest Strategy [8], and Metro Vancouver's Climate 2050 Framework [9].

2.0 Literature Review

2.1 The Urban Boundary Layer

The complex shape, structure, and thermal properties of metropolitan areas have a profound effect on the atmospheric conditions above cities [10]. In urban areas, the well understood atmospheric boundary layer (ABL) – the layer of the atmosphere nearest to the earth and which extends to approximately 0.8-1 km in height – is redefined as the urban boundary layer (UBL). The UBL is one of the least understood atmospheric regions, and thus is an area of considerable study in recent literature [10]. The UBL can be divided into two distinct layers: the roughness surface layer (RSL), which extends from the surface to about 2-5 times the average building height, dominated by spatially variable turbulent flow; and the inertial sublayer, a higher region of mostly homogeneous flow [10,11]. Within the RSL are two sub-layers: At the lowest level, the Urban Canopy Layer (UCL) occupies the space between the ground and the average height of the surrounding buildings. Above the average building height, a nameless, strong shear layer exists which is predominated by high winds and elevated turbulence and mixing [11].

Within the UCL, local turbulence has different characteristics from those seen in other layers. Local flow patterns are uniquely influenced by the changing surface roughness and the diverse thermal properties of urban materials within these regions [10]. Each unique local neighborhood microclimate within the UCL starts off in equilibrium with the surface beneath it. But as altitude increases, these small climate zones begin to mix, up through a transitional blending layer that eventually extends to the top of the RSL. At the top of the RSL and beyond, relative consistency of flow is achieved in the ISL [10]. These characteristics all play into the urban surface energy balance, which drives the atmospheric processes above [10].

Despite the challenges encountered in characterizing it, the UCL is the space within which humans spend most of their time, and thus is a microclimate that cannot be ignored. The behaviour of air flow within the UCL is important because it influences the movement of pollutants. Urban pollution often worsens in high temperatures brought on by the UHI, due to photochemical smog production. Thus, the influence of the UBL and the UHI on pollution formation and dispersion mean they are strongly linked to human health and comfort [1,4,11,12,13,14]. An improved understanding of the vertical atmospheric profile of urban neighborhoods would contribute meaningful information to the impact that urban design parameters have on air pollution management and pollution related morbidity and mortality.

2.2 Urban Heat Islands: Overview and Causes

The UHI is an atmospheric phenomenon that manifests as a region of warmer temperatures within and over urban areas compared to the temperature of surrounding rural areas [1,2]. Health Canada [2] notes that this effect usually occurs over large metropolitan areas where built surfaces absorb large quantities of solar radiation during the day. However, the EPA [1] states that the effect has been noted even over smaller cities and towns, though the size of the temperature effect declines as the urban area decreases in size. The existence of built-up urban features has been observed to cause temperatures that are 2°C to 12°C higher than non-urban areas [1,4,2], with the highest temperature differences occurring at night [1].

The behaviour, features, and causes of the UHI have been discussed in a wide variety of literature sources [10,11], including provincial [4] and national guidelines [1,2]. According to Giguere [4], the main contributors to UHIs are low vegetative cover, high proportions of impermeable surfaces, urban morphology, greenhouse gas emissions, anthropogenic heat, and thermal properties of surface materials.

A major side-effect of urbanization is the loss of vegetation, especially tree cover. As vegetation is removed during urbanization, it is often replaced by impervious materials like asphalt, concrete, and buildings. This loss of vegetation decreases ground shading and reduces cooling of the air by evapotranspiration [1,5,11]. Furthermore, increased imperviousness causes an increase in runoff and reduced penetration of stormwater into the ground and soil. Normally, heat in the air is dissipated by the evaporation of moisture from the ground when temperatures increase. However, when impervious materials replace the natural ground surface this evaporative cooling process is disrupted [4,5].

To combat the UHI, some regions have implemented urban greening policies to boost the proportion of vegetation within urban areas. Policies often encourage green infrastructure such as green roofs and walls on buildings. Green roofs have been demonstrated to be consistently cooler than other roof types in summer, even light-colored roofs [1]. Other approaches include municipal tree planting strategies [8,9], and discouraging the removal of trees on private property [5]. The existence of urban parks instead of buildings can also decrease the surrounding air temperature by up to 6°C [4]. Rain gardens, infiltration trenches, natural retention ponds, and constructed wetlands are accompanying tools used in greening strategies for improving permeability and managing stormwater runoff and flooding.

The thermal properties of common urban materials including albedo, emissivity, and heat capacity also play a role in the formation of UHIs. Albedo is a ratio indicating the proportion of solar radiation received by an object that is reflected back from the surface rather than absorbed [4,11]. Darker colored materials usually have a low albedo, meaning they absorb more solar radiation than they reflect, causing the object to heat up and by releasing that energy warm the surrounding area. Lesnikowski [5] identified the abundance of dark roofs on single family homes in Vancouver as a common problem contributing to UHI formation in the city's many historic neighbourhoods.

Thermal emissivity, on the other hand, is a measure of a material's ability to release heat back to its environment [1,11]. Emissivity is dependent on a material's finish and on the temperature of the surroundings, which influence the rate of energy release. High emissivity materials hold onto heat longer and may increase the heating load of a building, or increase the heat of the nearby environment [15]. The heat capacity of a material, defined as the amount of heat required to raise a given mass of material by 1°C [16], also plays a role. Generally, materials found in cities have a higher heat capacity than natural materials such as soil or sand. This results in downtown metropolitan areas that can absorb and store twice as much heat as their rural surroundings, on average [1].

2.3 The Role of 3D Structure and Urban Morphology

The impact of 3D urban morphology on air temperature in cities has been studied by a number of researchers in recent years [eg. 17,18,19]. A consensus exists in the literature that the existence of vegetative features – specifically trees – is negatively correlated with temperature [5,17,18,19,20]. Gage & Cooper [17] used LiDAR (Light Detection and Ranging), a remote sensing method, to perform hexagonal cluster analysis of land cover patterns in Colorado and found that temperatures were higher in clusters where mean building height exceeded mean tree height, and cooler where trees were on average taller than surrounding buildings. Tian et al. [19] noted that the ratio of the volume of vegetation to building volume played a significant role in urban temperatures in Beijing, but only in predominantly low-rise neighborhoods. In high-rise neighbourhoods, vegetation volume was less important than the orientation of buildings to solar radiation. Both of these studies support the importance of tall, mature trees for the shading properties they provide, a view maintained widely in the literature [1,4,5,11].

Building orientation and shape has been flagged as a major contributor to microclimatic temperature variation in cities. The orientation of buildings in relation to solar radiation and prevailing wind directions was noted to play a role in temperature of the surrounding air by Lesnikowski [5], and Tian et al [19]. Urban morphology features within the UCL such as urban canyons and sky view factor (SVF) are also key players in neighborhood microclimates [4,11]. Generally, deep urban canyons found in denser, high-rise dominated landscapes have low SVF, meaning that less solar radiation can reach the ground surface. Low SVF correlates with lower temperatures during the day, due to the shading provided by tall buildings [18,19]. However, these same high-rise, low SVF neighborhoods also had comparably higher temperatures at night [18,19]. In urban canyons, solar radiation that does find its way between buildings is reflected back and forth, often being absorbed, released, and then reabsorbed by building materials within the canyon. Anthropogenic heat emanating from buildings may also add heat to the landscape [1,4,18]. All of these factors act to retain heat within urban canyon regions at night, resulting in observed higher night time temperatures. In contrast, neighborhoods with shorter buildings and greater SVF, despite getting hotter during the day, had more effective surface radiative cooling from urban materials and thus cooled off more quickly at night [18,19].

2.4 Exploration of Vertical Temperature Profiles

Despite the growing body of research on the influence of 3D morphology on air temperature in cities, most research to date has focused on the spatial distribution of heat at the surface level of urban landscapes [5,17,18,19,20]. As pointed out in some studies [10,21,22,23], research that has measured or looked at the vertical atmospheric features of the UHI is limited.

A variety of methods have been used to investigate vertical temperature profiles. Gorlach et al. [22], used satellite data to estimate the approximate height of the UHI effect over Moscow to be as much as 1500m in the summer. Lokoshchenko et al. [23] measured the upper boundary of the UHI over Moscow using a mixture of radiosonde data and sensors affixed to a TV tower and mast. The latter study concluded that the UHI extended approximately 400m above the city, in contrast to the results found by Gorlach et al. [22]. This difference could be attributed to the low spatial resolution of the satellite data compared to radiosondes and weather masts. Sugawara et al. [24] used tethered balloons to investigate the vertical structure of a local cool island above a city park.

The methods used in the above studies come with limitations. Satellite data is low in resolution and useful only for large scales, making it unhelpful for understanding the microscale structure of local UHI effects [22]. Radiosonde data is complicated by the thermal inertia of the sensors, meaning they experience a slight delay in registering the actual temperature and cannot keep up as the radiosonde gains elevation. This leads to a slight overestimation of temperature [23]. Radiosondes are also difficult to precisely control, presenting a challenge for obtaining consistent, repeatable data [12,23]. And while the use of meteorological masts or other tall structures for affixing sensors to is feasible, researchers must consider the influence of building heat on sensors, and may also face both cost barriers and practical height limitations with regards to how far up they can record data [12,13].

Another approach to estimating and understanding the vertical structure of the UHI is through statistical modelling. Wang et al. [25], estimated the height of the UHI over Beijing using experimental modelling. The temperature difference between the city and a rural control area extended up to about 0.8km in the summer, and 0.5km in the winter. This is a similar height to that found by Lokoshchenko et al. [23], despite the different climatic locations. Barlow [11] provides an extensive review of progress in modelling of the UBL, including temperature phenomenon like the UHI. While modelling of the urban atmosphere has come a long way, models still lack precision due to an incomplete understanding of the processes within the UBL.

2.5 Studying the Urban Atmosphere with Remotely Piloted Aircraft Systems

RPAS are a relatively new tool being used in atmospheric investigations, having only been applied to vertical temperature investigations in a small number of studies, many of which are feasibility studies. The use of RPAS for the collection of vertical temperature data could eliminate many of the limitations encountered with other methods favoured by atmospheric researchers [12,13]. Small RPAS can bypass the barriers faced by conventional piloted aircraft in studying the lower urban atmosphere. RPAS can also be precisely controlled and do not encounter the location inconsistencies faced by radiosondes. Mounted sensors can remain in position long enough to remove thermal inertia errors. RPAS are also able to hover away from structures to eliminate building temperature interference. The relative low cost and ease of access to small RPAS enables their broader use within the research community. In a feasibility study by Masic et al. [13] a small, in-house designed multirotor RPAS apparatus was used to investigate vertical temperature profiles over Sarajevo, in the pursuit of a cost effective, flexible methodology for measuring atmospheric inversions over an urban area. This feasibility study captured temperature changes over a vertical distance of 1km, and effectively identified temperature inversions. Adkins et al [12] presented a methodology for using “meteorologically instrumented” RPAS to investigate temperature, pressure, and wind speed within the UBL. However, the authors also noted a current limitation of RPAS: that the existence of tight regulations on flights within cities can restrict the breadth of available measurements, especially height. Other studies have successfully investigated other meteorological parameters in the ABL using RPAS, though not in relation to the UBL [21,26,27]. Nonetheless, these studies attest to the reliability of RPAS as a research tool for the atmospheric sciences.

3.0 Methods

This project utilized an experimental research design. The methodology included direct atmospheric profile measurements, results analyses and the graphical and numerical presentation of atmospheric temperature profiles. Four locations were chosen within and around downtown Vancouver in order to capture a variety of different surfaces, materials, and urban morphologies. All locations fall within a fairly small geographic area of approximately $10km^2$, which allows for an analysis of variability due to site features rather than horizontal distance between locations. Locations were chosen to represent the following four types of urban environment.

1. **Mediumly urbanized**. Mix of low and higher rise buildings and streets, with moderate vegetation, grass/park and tree cover, and a higher proportion of lighter colored pavement or gravel..

2. **Highly urbanized**. Many tall and medium sized buildings and streets, mixed residential/commercial, with lots of asphalt, concrete, and man-made surfaces, with little vegetation or tree cover.
3. **Urban with UHI mitigation features**. An urbanized location with buildings, streets, and man-made features, but also features such as green roofs or walls, parks/grass/gardens, and low albedo materials.
4. **Urban parkland**. A highly vegetated area with a large proportion of trees/grass/shrub or other natural features, and minimal man-made features.

The sites chosen to represent each of the above four categories are shown on Google Earth satellite images included below in Figure 2. Exact locations of each site are noted in the corresponding figure caption.

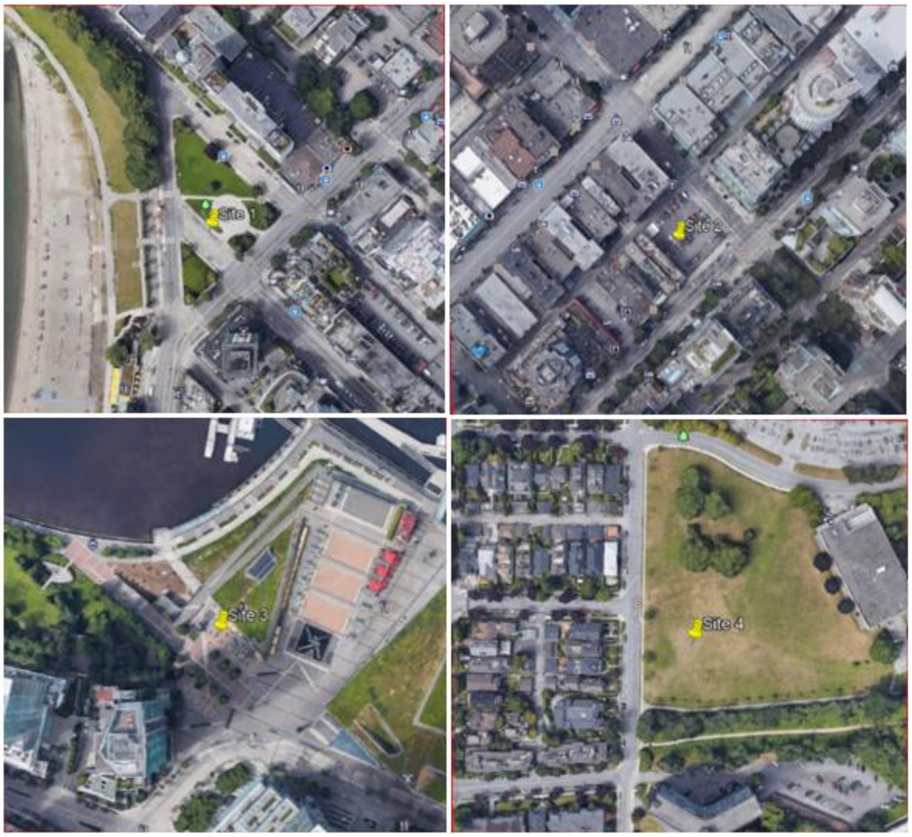

Figure 1: Google Earth Image of all sites – Site 1 Denman St. and Morton Ave (top left); Site 2 - Seymour St. and Nelson St. in parking lot #83 (top right); Site 3 - Jack Poole Plaza near the Convention Centre West (bottom left); Site 4 - SW Vanier Park at Chestnut St. and Creelman Ave (bottom

As all of downtown Vancouver is within Class C controlled airspace, all flights must abide by Transport Canada regulations, and certified pilots must request individual approval for their flights from NAV CANADA and the Harbour Control Tower. Additionally, flights carried out in municipal and provincial parks or on private property require written permission from the property owners or managers.

At each testing site two RPAS were employed to capture temperature data at ground level and four different altitudes. Each RPAS rested at ground level (1m from ground surface) for a minimum of 10 minutes, launched and then hovered at two separate altitudes for 6-10 minutes per altitude. Data was collected at the following elevations above ground: 1m, 20m, 40m, 70m, and 120m. In Canada, 122m is the maximum allowable altitude for drone flights without a special flight operations certificate, which was not obtained for this study. In some cases, pilots received individual height restrictions of 90m, so in those cases the maximum height obtained was limited by NAV CANADA permissions. The range of altitudes chosen was intended to capture the top of the urban canopy layer in all locations.

Hovering the RPAS at two set altitudes rather than ascending the entire distance at a set velocity allowed sufficient time for the temperature sensors to adjust and overcome any thermal inertia. TMCx-HD Air/Water/Soil Temperature Probes were used, which have a response time in air of two minutes. The RPAS used in this study were the DJI Air, Mavic 2 and Phantom 4 Pro. All are small, multi-rotor (4) drones with a typical maximum flying time of 20 minutes. Battery life informed the 6-10 minute hover time, which allowed ample time for the sensor to adjust, plus a safety margin. Each sensor was connected to a HOBO U12-013 data logger, and housed in a small, lightweight metal dish. The housing apparatus was approximately 8cm deep, with the data logger and sensor resting on a 2cm thick layer of foam to provide insulation from any heat produced by the body of the RPAS. The sides of the metal housing also provided protection from direct solar insolation and air currents created by the rotor blades. Each sensor apparatus was secured to the underside of the RPAS and launched from a small 1m high platform.

Data was collected twice on each sampling day: at 10am and 3pm. These times were intended to capture temporal variation in air temperature over the course of the day. Testing was intended to be completed over a period of 8 months to capture seasonal variation in the atmospheric temperature profiles. Temperature variation between sites was expected to be more pronounced in the summer, however, the literature implies that the UHI effect still exists in the winter months, though to a lesser degree [1,22,23]. Data collection over multiple seasons thus allowed for observation of seasonal variability and an analysis of whether the UHI effect was present and persistent across seasons. Originally, data was intended to be collected in late summer, winter, and spring. Unfortunately, prior to the last round of data collection in the spring, a safety issue related to the ability of the drones to carry the sensor apparatus payload was encountered. This issue compromised the ability of the research team to safely complete the last round of flights. As a result, data was only collected in late summer and winter.

Data collection dates were targeted to capture temperatures representative of typical seasonal weather in Vancouver: late summer (warm, sunny weather), winter (cold, overcast weather). Late summer was selected rather than mid summer due to the constraints of the academic year, which runs from September to April. Late summer measurements were selected to target warmer days resembling summer temperatures as much as possible. Typical weather in Vancouver was defined as an approximation of average ground level atmospheric temperatures for the first and second month of the seasonal period, as outlined in Table 1.

Table I: Average Seasonal Temperatures for Vancouver Based on the First Two Months of Each Season [28]

Season	Duration	Targeted Sampling Time	Ave Temp (ºC)
Late Summer	Sep. 1 – Nov. 30	September to early October	15-20
Winter	Dec. 1 – Feb. 28	Mid January	5-10

Photographic documentation and written observations of each site at the time of testing was captured, describing the features of the site and the weather conditions. Weather data was retroactively collected from the nearest Environment Canada weather station (Vancouver Harbour CCS) for each launch time as a double check, including: temperature, relative humidity, wind speed and wind direction [29]. A ±4°C margin of error was considered acceptable.

To quantify the materials, surfaces, and urban morphology of each site, the site area was defined as a 0.25km x 0.25km square centered over the launch location. Satellite images from Google Earth, in combination with data from the City of Vancouver's Urban Forest Strategy [8], were used to approximate the percent tree canopy coverage within each area, as well as the percent coverage by impervious surfaces. Google Earth satellite images were also used to approximate the amount and type of different kinds of surface materials within each site area. Types of surfaces considered include roof color (dark, light, or green roofs), asphalt, concrete, gravel, paving stones, grass/low vegetation, and trees. Corresponding albedo and emissivity values for each material type was also noted. Finally, the intensity of urban morphology was quantified based on average building height, observed density of buildings, and the number of low (under 7 floors), medium (7-15 floors), and tall (over 15 floors) buildings present within the site area. Buildings that were more than 50% within the site bounds were included in the building count.

Collected data was compiled and displayed visually using graphs and tables for comparison and analysis. Air temperature at each altitude was determined by taking the average of temperatures logged by the sensor after the first 2.5 minutes sensor adjustment period at each altitude. For quality control, the first and last 30 seconds of hovering at each altitude was excluded from data consideration. Average air temperature was then plotted against altitude at each site and for each launch to obtain a graphical representation of the environmental lapse rates. The lapse rate at each site and for each date and launch time were also compared against the dry and wet adiabatic lapse rates (DALR and WALR, respectively) to determine atmospheric stability. Vertical temperature profiles were compared between sites and analyzed based on the characteristics of each site using a simple observational analysis. The goal was to characterize the vertical temperature profile of each location, understand if and how it varied between sites, and then explore possible correlations between the characteristics of each site and the temperatures profiles found there.

4.0 Results

4.1 Site Characterization

Each of the four sites was characterized according to the methods described previously. A summary of site characteristics is included in Table 2. This section describes the results of each site's characterization process.

Site 4, which was located in Vanier Park and chosen to represent the greenest and least urbanized area, had the highest percentage tree canopy (20%) and vegetation coverage (49%) of all the sites. Site 4 also had the lowest overall building height, with no tall buildings and only 1 medium height building to the south end. Site 4 was adjacent to a residential neighbourhood which account for approximately 40% of the site area. The remainder of the site consists of an urban park with grass and trees. The height of the UCL (i.e. the average building height), was calculated to be 10.1m, though this may be skewed slightly due to the single 14 story building. All other buildings were 1-3 stories tall. Site 4 is located about 0.5km from the Burrard Inlet to the north. Despite having the most vegetation coverage, Site 4 did not have the lowest proportion of impervious surfaces, or the lowest proportion of dark roofs and asphalt. Dark roofs and asphalt have the lowest albedos of those identified, and some of the highest emissivity values. In fact, Site 4 had the second highest proportion of dark roofs (25%), and the second lowest proportion of asphalt (21%) of all the sites.

Table II: Summary of Site Characteristics at all Four Testing Locations

	Site 1 - English Bay		**Site 2 - Parking Lot**		**Site 3 - Convention Centre**		**Site 4 - Vanier Park**			
General Features	Site data	Vancouver data	Site data	Vancouver data	Site data	Vancouver data	Site data	Vancouver data		
% Tree Canopy Coverage	9	10-20	12	<5	11	5-15	20	15-20		
% Vegetation Coverage (all types)	21	-	16		29		49			
% Impervious Surface Coverage	59	50-75	83	>75	27	25-50	50	25-50		
Urban Morphology Features										
Observed Density	Medium		High		Medium- low		Low			
Average Building Height (m)	24.5		22.3		81.7		10.1			
Tall Buildings (>15 floors)	4	21%	6	16%	3	60%	0	0%		
Medium Buildings (7-15 floors)	1	5%	2	5%	0	0%	1	3%		
Low Building (<7 floors)	14	74%	30	79%	2	40%	33	97%		
Total # Buildings	19		38		5		34			
Surface Material Types:	%								Albedo	Emissivity
Dark roof	15%		37%		3%		25%		0.1	0.92
Light roof	8%		14%		4%		1%		0.4	0.9
Green roof	2%		3%		14%		0%		0.2	0.93
Asphalt	30%		27%		10%		21%		0.08	0.95
Concrete	6%		5%		10%		3%		0.225	0.8
Gravel/Paving Stones	2%		0%		23%		2%		0.15	0.9
Grass/Low Vegetation	10%		1%		4%		29%		0.25	0.93
Trees	9%		12%		11%		20%		0.165	0.97
Other	19%		1%		22%		1%		N/A	N/A

Site 2 was located in a parking lot at the intersection of Nelson St. and Seymour St., in the heart of the commercial district of downtown. This site was selected to represent the most urban and man-made landscape, with the highest predicted risk for UHI effects of the four sites. Site 2 had the most impervious surface coverage (83%) and the lowest vegetation coverage (16%). Most of the vegetation coverage was provided by trees, concentrated to the southeast corner of the site where all of the tall buildings – primarily high-density residential apartment complexes – were located. Site 2 had the highest number of total buildings (38), and the highest number of tall and medium height buildings. Despite this, the average building height of Site 2 was only 22.3m, due to the large quantity of low buildings (30) also present. The northwest two-thirds of Site 2 was comprised mostly of these low, commercial type buildings with flat, dark roofs and almost no trees or vegetated surfaces. Interestingly, the tree canopy coverage at Site 2 (12%) was not the lowest of the four sites, having a slightly greater proportion of tree canopy coverage than both Sites 1 (9%) and 3 (11%). It should be noted that because percent coverage of materials was estimated with a grid method using Google Earth images, there is a chance the difference is due to estimating error. For this reason, Sites 1, 2 and 3 could be considered to have approximately the same amount of tree canopy coverage. Despite the similar tree coverage, Site 2 still boasts the lowest total proportion of vegetation.

Sites 1 and 3 fall somewhere in the middle between the above two mentioned sites, with varying vegetation and material coverage. Site 1 was located in a small green area 120m to the east of English Bay Beach, near the intersection of Morton Ave and Denman St. Site 1 is the most exposed to prevailing ocean breezes, which originate from the west and northwest in the summer. This site is located in the West End, an affluent, well vegetated residential mixed zoning neighbourhood with many restaurants and retail stores. Site 1 had the lowest tree canopy coverage (9%), partially due to the large amount of beach included in the site area, and the site's proximity to several blocks of commercial zoning to the southwest with lower-than-average tree canopy coverage [8]. Site 1 has the second lowest overall vegetation coverage (21%) after Site 2, and the second highest impervious surface coverage (59%). The building distribution of Site 1 is mixed, having 19 total buildings within its area, 4 tall, 1 medium height, and 14 low height. The average building height at Site 1 was 24.5m.

Finally, Site 3 was chosen because of the two large green roofs within its bounds, in an effort to observe the mitigation potential of such features. Site 3 was the northern most site, located just west of the Vancouver Convention Centre West Building. This site was the closest to the ocean, at only 70m away, but is somewhat sheltered from prevailing winds that blow from the west and northwest and which would have to pass through the dense downtown area first. This site had the lowest overall number of buildings (5). Despite the small number of buildings, three of the buildings were either dense high-rise apartment complexes or commercial skyscrapers. Average building height for the entire site was 82m, however, all buildings were clustered in the southwest corner. If broken down, the average building height in the southwest corner is 129m, and for the rest of the site, 10m.

Site 3 has the second highest percent vegetation coverage of the four sites (29%). Most of the vegetation coverage at this site is from lower vegetation such as grass covering the green roofs, while tree canopy coverage at Site 3 is the second lowest overall (11%). Site 3 also boasts the lowest proportion of impervious surfaces (27%), however, 23% of the site is covered by paving stones, with a lower degree of permeability compared to gravel and surface vegetation.

4.2 Summer Vertical Profiles

Vertical temperature profiles varied significantly between all four sites in the summer time, both during the morning and afternoon launch times. Variation existed between the individual lapse rates at each site, as well as in the temperatures between sites. The maximum difference in air temperature (3.36°C) occurred in the afternoon at 40m, between Sites 1 and 2. Surface temperatures also varied between sites, with the largest difference (3.06°C) occurring between Sites 1 and 4. In the morning time, overall variation in air temperatures between sites was lower, and temperatures appeared to converge at the highest altitude of 120m. This is in contrast to the afternoon, where variation between sites was slightly greater overall, and temperatures did not converge at the 120m mark, though they did appear to start moving closer together. Vertical profiles from all sites are shown in Figure 3 and Figure 4.

Site 2 – the parking lot – displayed the warmest air temperature overall in both the morning and afternoon, though the surface temperature at Site 2 was only the second highest in the morning, and the third highest in the afternoon. Interestingly, the park location at Site 4 had the highest surface temperatures during both launches. At altitude, however, air temperatures at Site 4 were generally lower, and remained lower even through the increasing heat of the afternoon.

Both Site 2 and Site 4 displayed minimal change in atmospheric structure from the morning to the afternoon, but did increase in temperature, as shown by a shift of the vertical profile to the right. At Site 4, the sharp decrease in temperature seen from the surface to the lower altitudes is likely exaggerated due to requirement for the launch site to be on the sidewalk next to the park rather than in the park, due to launch restrictions in municipal parks, but may suggest an unstable atmosphere. Once in the air, the RPAS moved over the park and both the morning and afternoon profiles of Site 4 show a low-level inversion at 40m in the morning, sinking to 20m in the afternoon. This inversion decreased in thickness by the afternoon. Conversely, the parking lot location (Site 2) was the only site which retained a stable atmosphere throughout the day and did not exhibit any kind of obvious atmospheric inversion, instead having a possible, very minor ground-based inversion in the afternoon. A ground-based inversion occurs when cooling from the surface is trapped beneath a warmer layer of air above it. Figures 5 and 6 show examples of the vertical profiles of Site 2 and 4, respectively, in the afternoon, plotted against the DALR and the WALR to determine stability.

In contrast to Site 2 and 4, the Convention Centre site (Site 3), showed considerable change throughout the day. In the morning, Site 3 was the coolest site through almost its entire vertical height, and was nearly the coolest at the surface; being less than 0.1°C warmer than the coolest site (Site 1). The morning atmospheric profile at Site 3 was unstable low in the atmosphere, with a considerable inversion layer at 40m and above. Site 3 also had the lowest air temperature measured that day at 15.63°C. However, in the afternoon the atmospheric temperature profile of Site 3 changed considerably. At the surface level, Site 3 was the coolest at 20.0°C, but once in the air was the second warmest site overall. This site also displayed a ground level inversion to 20m, followed by a fairly steady temperature through 40m and 70m, with a slight uptick in temperature to 120m. This slight increase in the upper part of the measured atmosphere may indicate the beginning of a higher altitude inversion that was beyond the reach of the data collected for this study.

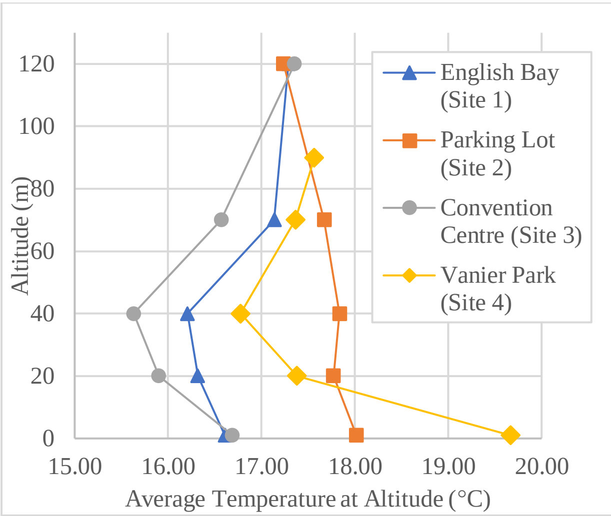

Figure 3: Combined vertical profiles of the atmosphere at all sites, morning launch (10am), summer

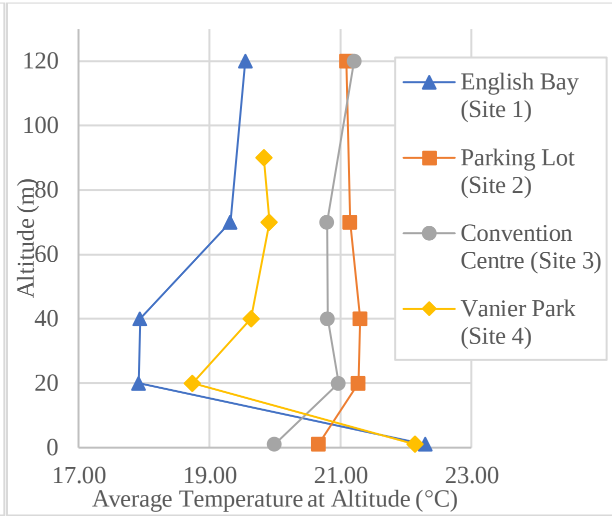

Figure 4: Combined vertical profiles of the atmosphere at all sites, afternoon launch (3pm), summer

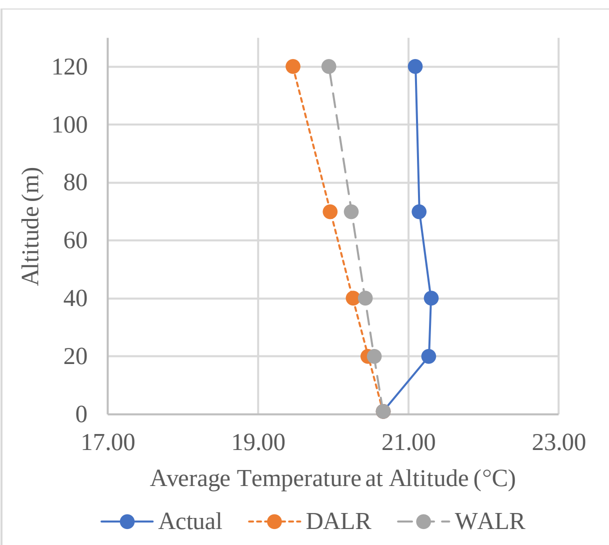

Figure 5: Vertical profiles of atmosphere at Site 2 during the afternoon launch, summer, with accompanying DALR and WALR

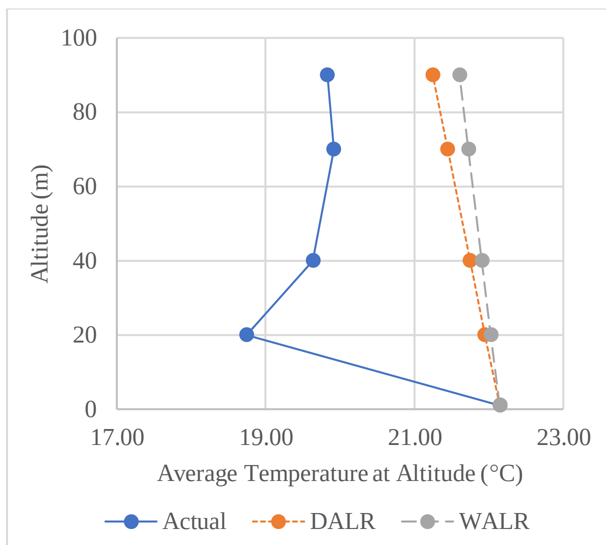

Figure 6: Vertical profiles of atmosphere at Site 4 during the afternoon launch, summer, with accompanying DALR and WALR

Site 1, at English Bay, was also peculiar compared to the other sites. In the morning, this site was one of the cooler sites, with a similar atmospheric structure to Site 3, albeit warmer by about 0.6°C. In the afternoon, the surface temperature of Site 1 became the warmest surface location overall, whereas the air above Site 1 was the coolest of the four sites. The temperature of Site 1 decreased from 22.30°C at ground level to 17.92°C at an altitude of 20m, a drop of over 4.38°C through a very unstable region. From the 20m point, air temperature was steady for a short time, and then entered an inversion from 40m and beyond. Surface and atmospheric temperatures with corresponding altitudes for the summer launches, which were completed on September 30, 2020, are provided in numerical form in Table 3.

Table III: Numeric Temperature Profile Data vs. Altitude at all Sites, Summer Launches, Sep. 30, 2020

	Site 1 – English Bay		Site 2 – Parking Lot		Site 3 – Convention Centre		Site 4 – Vanier Park	
Morning, 10am	Average Temp (°C)	Altitude (m)	Average Temp (°C)	Altitude (m)	Average Temp (°C)	Altitude (m)	Average Temp (°C)	Altitude (m)
	16.6096	1	18.0162	1	16.6880	1	19.6657	1
	16.3179	20	17.7698	20	15.9016	20	17.3810	20
	16.2088	40	17.8379	40	15.6321	40	16.7762	40
	17.1371	70	17.6716	70	16.5689	70	17.3627	70
	17.2882	120	17.2377	120	17.3539	120	17.5657	90
Afternoon, 3pm	Average Temp (°C)	Altitude (m)	Average Temp (°C)	Altitude (m)	Average Temp (°C)	Altitude (m)	Average Temp (°C)	Altitude (m)
	20.6641	1	20.6641	1	19.9952	1	22.1456	1
	21.2756	20	21.2756	20	20.9737	20	18.7433	20
	21.3021	40	21.3021	40	20.8077	40	19.6358	40
	21.1457	70	21.1457	70	20.7978	70	19.9151	70
	21.0957	120	21.0957	120	21.2090	120	19.8303	90

4.3 Winter Vertical Profiles

Overall, variation in the vertical temperature profiles between sites during the winter time was much less substantial compared to summer variations. Small temperature differences between the site profiles were present, but the atmospheric structure above all of the sites was similar. In the morning all profiles were warmest at the ground surface, ranging from 5.55°C at the Convention Centre (Site 3) to 6.31°C at English Bay (Site 1). As height increased, temperatures decreased most steeply in the first 20m of the atmosphere, indicating an unstable lower region. At 40m, all profiles experienced a slight decrease in their lapse rates, but still continued to decrease in temperature with elevation, through to the maximum recorded height of 120m. At 120m, Site 4 had the lowest air temperature (4.06°C), and Site 1 continued to have the highest air temperature (4.89°C). Throughout the entire vertical profile, temperature differences between sites remained fairly steady. A graphical representation of the vertical profiles at all sites are included in Figures 7 and 8.

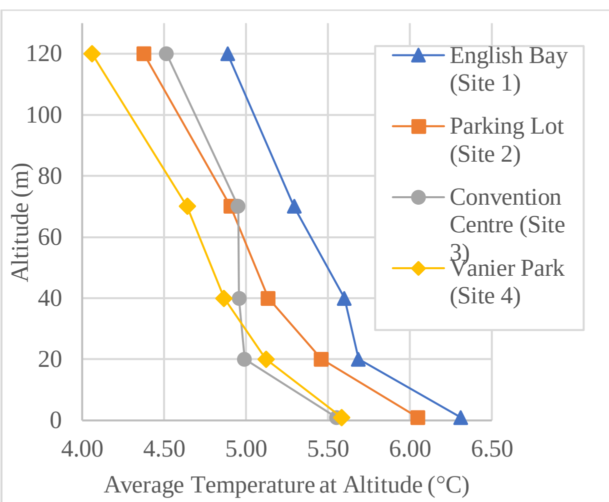

Figure 7: Combined vertical profiles of atmosphere at all sites during the morning launch (10am), winter

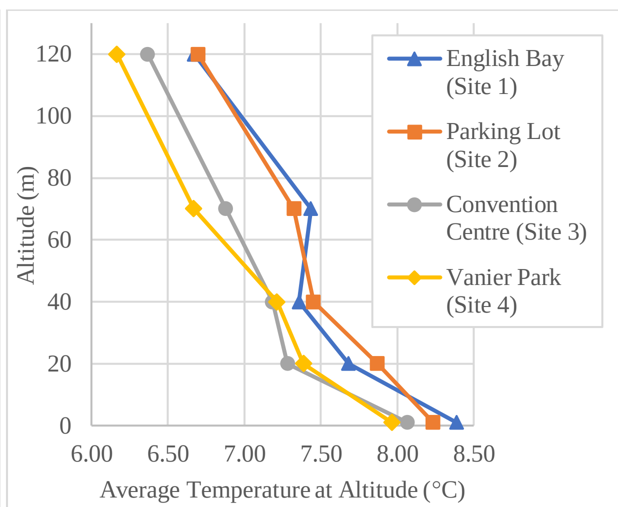

Figure 8: Combined vertical profiles of atmosphere at all sites during the afternoon launch (3pm), winter

In the afternoon, profiles were similar to the morning, with a bit more variation between sites in the 20-70m layer. Beyond 70m, all temperature profiles again continued to decrease until the 120m altitude. Surface temperatures in the afternoon were slightly closer together, ranging from 7.96°C at Vanier Park to 8.39°C at English Bay. At 120m, temperature varied from 6.17°C at Site 4 to 6.7°C at Site 2. During both the morning and afternoon launches, Site 4 had the lowest overall temperature. Site 1 at English Bay was the warmest of the four sites in the morning time. In the afternoon, Site 1 and 2 were warmest, having very similar temperature profiles. Site 1 also displayed the only potential inversion observed during the winter launch, though it was very slight. Due to the small difference in temperature (0.08°C) between 40m and 70m over Site 1, it is uncertain whether this was truly an inversion or merely a localized perturbation in temperature.

Stability of the atmosphere seemed fairly consistent across sites. In both the morning and afternoon, an unstable layer existed closest to the ground, up to about 20-40m. In the middle reaches of the measured atmosphere (20-70m), stability increased briefly, with all sites experiencing a layer of stability somewhere in this region. In the upper section of the measured column, all profiles again became unstable or conditionally unstable. Surface and atmospheric temperatures with corresponding altitudes for the winter launches, which were completed on January 29, 2021, are provided in numerical form in Table 4.

Table IV: Numeric Temperature Profile Data vs. Altitude at all Sites, Winter Launches, January 29, 2021

	Site 1 – English Bay		**Site 2 – Parking Lot**		**Site 3 – Convention Centre**		**Site 4 – Vanier Park**	
Morning, 10am	Average Temp (°C)	Altitude (m)	Average Temp (°C)	Altitude (m)	Average Temp (°C)	Altitude (m)	Average Temp (°C)	Altitude (m)
	6.3105	1	6.0486	1	5.5512	1	5.5846	1
	5.6856	20	5.4596	20	4.9903	20	5.1222	20
	5.5993	40	5.1363	40	4.9581	40	4.8666	40
	5.2933	70	4.9068	70	4.9522	70	4.6418	70
	4.8868	120	4.3760	120	4.5147	120	4.0600	120
Afternoon, 3pm	Average Temp (°C)	Altitude (m)	Average Temp (°C)	Altitude (m)	Average Temp (°C)	Altitude (m)	Average Temp (°C)	Altitude (m)
	8.3872	1	8.2352	1	8.0663	1	7.9644	1
	7.6824	20	7.8700	20	7.2830	20	7.3877	20
	7.3572	40	7.4531	40	7.1837	40	7.2142	40
	7.4352	70	7.3243	70	6.8779	70	6.6698	70
	6.6726	120	6.6968	120	6.3680	120	6.1673	120

5.0 Discussion

5.1 Summer Vertical Profiles

An examination of the data from the summer testing day revealed some results that aligned with the hypothesis of the researchers, and some results that were unexpected. In this section, the observed influence of site features on vertical profiles will first be discussed for the morning flight, followed by the afternoon flight observations, and finally a review of general observations for the entire day.

Overall, Site 2, which had the highest proportion of impervious surfaces, the lowest proportion of total vegetation, and the greatest number of buildings, consistently had the warmest air temperature. This aligns well with the consensus in the literature that local warming is caused by the replacement of vegetation with low albedo impervious surfaces like asphalt and dark colored roofs [1,4,5]. In fact, in addition to having the highest overall number of buildings, Site 2 also had the greatest proportion of dark colored roofs, at 37%, and the second highest proportion of asphalt, at 27%. Both asphalt and dark roofing material have very low albedos, 0.08 and 0.1, respectively, meaning they absorb most of the solar radiation they receive. Once absorbed, these two materials also have fairly high emissivity rates (0.95 and 0.92, respectively), and are thus quite efficient at emitting heat back to the atmosphere to warm their surroundings.

Past research notes that the UHI effect is greatest at night, when man-made materials emit heat stored during the day back into the air in the absence of solar radiation, preventing affected areas from cooling overnight as much as they would normally [5,18]. The comparatively warmer morning surface and air temperature of Site 2 in this study support this theory, suggesting that the dense urban landscape and high number of tall buildings at the site insulated the local atmosphere from normal cooling. In comparison, the three other sites had a smaller total number of buildings, as well as a smaller number of tall and medium height buildings. Other research also noted the effects of tall buildings on local heat. Two studies identified that temperatures were higher where average building height was greater, noting that this effect was stronger than the effect of vegetation and tree cover in such neighborhoods [17,19]. Site 2 was also farthest from the Burrard Inlet, which may have played a role in reduced nighttime cooling ability compared to the more exposed sites.

Site 2 did not have the warmest surface temperature. In the morning, Site 4 (Vanier Park) was considerably warmer at the surface than Site 2, and in the afternoon, Site 2 had a lower surface temperature than both Site 4 and Site 1. Site 4's surface warmth is almost certainly due to the need to locate the launch area immediately next to the park on the concrete sidewalk because of RPAS launch restrictions within municipal parks. The sidewalk is surrounded by open grass and asphalt roads with no shading from trees. Once launched, the drone assembly was moved over the park for the remainder of altitudes.

Despite the warm surface temperature of the Site 4 launch location, once the drone was positioned over the park the air temperature at 20m declined by 2.29°C, making it ultimately lower than the air temperature of Site 2 by 0.39°C. This cooling trend continued to 40m, where Site 4 was 1.06°C cooler than Site 2 at 40m. This lower temperature suggests that the park has a cooling effect in the air above it, despite the fairly similar proportion of asphalt within the site area (27% at Site 2, 21% at Site 4). Despite being cooler than Site 2, the park was still warmer overall in the morning than Sites 1 and 3. This temperature difference may be attributable to the high number of low-rise buildings with dark roofs in the block adjacent to Site 4, or t he cooling influence of the inlet on Sites 1 and 3.

Sites 1 and 3, which were the two coolest in the morning, had similar surface temperatures and exhibited similar vertical temperature profiles. Both sites were located quite close to the inlet and thus were likely influenced by the cooling effect of ocean, whereas Sites 2 and 4 are comparatively more protected. Gage & Cooper [17] noted a similar cooling effect in locations dominated by water. Ultimately, even with similar exposure to water, Site 3 at the Convention Centre had the coolest morning air temperature of all the sites. Proximity to the inlet and the higher proportion of vegetation at this site, including the large expanse of green roof on the nearby Convention Centre and restaurant are the most likely cause of this cooler temperature. These factors would have aided in radiative and evapotranspirative cooling during the night.

Vertical temperature profiles at each site changed considerably between the morning and afternoon test flights. As expected, temperatures at all sites warmed by several degrees. In the afternoon, the park at Site 4 appears to have retained its cooling effect in the air above the site. For the same reasons noted earlier, the surface temperature at Site 4 was quite high, but once above the park, the air remained cooler than both Sites 2 and 3. Site 4 remained cooler even at height, whereas Sites 2 and 3 experienced additional warming at higher altitudes compared to the morning. This suggests that the cooling effect of the park is persistent throughout the day, a notion supported by the literature [1,4,18]. The air was coolest immediately above the park at an altitude of 20m, after which it warmed slightly but still remained cooler overall.

Site 2 continued to have the warmest temperature in the afternoon, however its surface temperature dropped to third place, at 20.66°C. This cooler surface temperature is likely due to shading provided by surrounding buildings, a finding supported by other studies [18,19]. Visual observations from the site confirmed the presence of shading. Despite the cooler ground surface, the air above Site 2 was quite warm, indicating that the cooling effect experienced at ground level did not extend up into the UCL and RSL. In fact, the urban warming effect observed at Site 2 appears to have extended all the way up to the maximum measured altitude of 120m. With a calculated UCL height of 22m in this location, the warming effect thus extended beyond the tallest local buildings and as far up as the uppermost reaches of the RSL (calculated to be 110m). The high-altitude extent of warming could be attributed to a number of factors: trapped solar radiation within the urban canyon, anthropogenic heat released by the surrounding tall buildings through the height of the canyon and above, or the thermal properties of the building materials and facades.

Another result of interest from the afternoon test is the change experienced at the Convention Centre (Site 3). Whereas Site 3 had the coolest morning air temperatures, by the afternoon this Site's vertical temperature profile had shifted dramatically to the right, warming by 5.07°C at 20m, and 5.18°C at 40m. This is in contrast to the other sites, which warmed by 1.5-3.5°C at most. Given the higher proportion of vegetation at this site, the presence of the large green roof, and the cooling effects observed in the morning, this result was unexpected. The high degree of warming experienced at this site could be due to a horizontal advection of heat caused by the predominant wind direction. Being a coastal city, summer winds in Vancouver blow predominantly from the west and northwest [30], driven by sea breeze circulations. This meteorological phenomenon draws cooler air from the ocean towards the warmer regions over land, often becoming more pronounced in the afternoon and early evening [31]. A mild westerly wind direction is confirmed by observations recorded at the test sites, though wind data from the Vancouver Harbour CCS weather station was not available to confirm this [29]. Observations note that wind was calm in the morning, and increased slightly from the west in the afternoon. A westerly wind coming off the ocean would first blow across the warm interior of downtown and gain heat before blowing across Site 3 on the easternmost side of the downtown peninsula.

This warmer air could displace cooled air related to the surface features of Site 3. A similar phenomenon was noted by Pigeon et al. [32], who observed heat fluxes in a European coastal city during a period of afternoon sea-breezes, noting that horizontal advection was the dominant process over vertical thermal advection processes at that time.

Two observations support the theory that horizontal advection is causing the increased temperature noted at Site 3. First, the section of downtown immediately east of Site 3 is dominated by high commercial skyscrapers averaging around 80m in height. This matches well with the extent of the warm air column, which reaches up to at least the 120m mark. When wind forces are acting on an urban surface, a plume of warmer air may be advected downwind of the city, which can expand beyond the height of the original layer from which it originates [11]. Second, Site 1, which is located on the opposite side of the downtown peninsula, had considerably cooler air temperatures than most of the other sites. Site 1 would be situated in the direct path of the dominant sea breeze, which may explain why the air was so much cooler at this site, despite its higher proportion of impervious surfaces and low proportion of tree canopy coverage. In fact, the afternoon surface temperature of Site 1 was actually the highest of all four sites, which makes sense given its high degree of impermeability and relative lack of shading from trees. Site 1, however, then displayed the greatest drop in temperature between altitudes, dropping from 22.30°C at the surface to 17.92°C at 20m. This could be due to the inflow of ocean air just above the surface which acts to cool the atmosphere considerably. This evidence seems to support the flow of air across the city in a west to east direction.

Interestingly, despite the warmth of the air column, the surface temperature at Site 3 was the coolest of the four sites in the afternoon. It is unlikely that this surface cooling was due to shading from tall buildings, based on the small number of buildings present which are all far enough away to provide only minimal shading for the time of day. This may point to the fact that the high proportion of vegetation and the green roof at Site 3 were doing their job to keep the surface cool, but were overshadowed at higher altitudes by the horizontal movement of the plume overhead.

In addition to the local effects at each site discussed above, some general observations for the entire study area were also noted. First, air temperatures appeared to converge with increasing altitude in the morning, but not in the afternoon. These observations match well with descriptions of the urban atmosphere provided by Barlow [10]. In the morning, the surface of each site was cooler, therefore the unique warming effect of the local area would be expected to extend up only a short distance. However, as the surface was heated by solar radiation over the course of the day the vertical extent of warming above the site would be expected to increase. In either case, once a certain height is reached, local atmospheric forcings become negligible and air temperature should become homogenous due to mixing in the upper reaches of the UBL [10]. This homogeneity was observed at the convergence point in the morning profiles. In the afternoon, however, the reach of the increased warming effects from local features appears to have extended further into the atmosphere, as expected.

Finally, all sites except the parking lot exhibited what could be an atmospheric temperature inversion at around 40m. This inversion persisted into the afternoon at Sites 1 and 4, which were the western most sites, but disappeared at Site 3 in the afternoon, potentially overtaken by horizontal advection processes. Environment Canada did not have historical information available on inversions over Vancouver at the time of testing to confirm this observation. A frontal inversion caused by the collision of cool ocean air with warmer air over the city [33] is possible, and would align with the theory for why such a cool layer of air existed at 20m and 40m over Site 1 into the afternoon.

5.2 Winter Vertical Profiles

During the winter test day variation between vertical temperature profiles was much less pronounced. All four sites showed a fairly similar vertical profile in both the morning and afternoon, which was warmest at the surface level and decreased more or less steadily with height. Site 3 exhibited the greatest level of variation in the middle region with a period of steady temperature occurring from 20m to 70m, but otherwise had a similar profile in the lower and upper atmosphere. This could be a result of the eastern exposure of Site 3 to the warmer air above the inlet, which experiences an easterly prevailing wind direction in the winter. This is opposite to the prevailing wind direction experienced in the summer, due to a reversal of the temperature gradient over land and sea [31].

In the afternoon, all four sites again displayed a fairly similar atmospheric structure, with a zone of slightly increased variation in temperature between sites from 20m-70m. The upper bounds of the UCL, as determined by the average building height, was calculated to occur within this range at all sites. Therefore, it is possible that this slight variation could simply be due to the zone of increased mixing and turbulence that occurs in the upper half of the RSL.

It is possible that the thermal properties of the various surface materials and vegetation at each site were having a minor effect on the air temperature above, even in the winter. For example, Site 2 continued to be on the warmer side, and Site 4 remained on the cooler side. Since the heat capacity of materials is greatly reduced in the winter due to colder ambient temperatures and increased cloud cover interfering with solar radiative gain, it is expected that any UHI effects, if they existed, would be significantly reduced. However, site variations were very small and it is therefore also possible that observed variations were merely due to random fluctuations in the atmosphere. For this reason, it is not possible to say with certainty that local urban features had an impact on temperature variation between sites during the winter season. It is also uncertain whether the UHI effect was present in the study area at all during the winter. The inclusion of a distant data point outside of the larger Vancouver metropolitan area may have helped determine if a UHI was present, and should be included as a control point in future research.

Some sources of error may have existed during both testing days, but it is expected that they had minimal impact on the results. Firstly, some systematic error may have been introduced by imprecise instrumentation (i.e. the temperature sensors and drones). Due to the format of this experiment and availability of instruments and RPAS, it was not possible to compare the instrumentation used in this study with other instruments to ensure accuracy or precision. However, any imprecision that might exist would be carried through to all of the results and should not influence the temperature variance observed between altitudes or sites. Some error may have also been introduced due to time delays between launches at some of the sites. For example, in the winter, flights at Site 3 had to be staggered due to a malfunction with one of the drone sensors that prevented the flight from being controlled in a safe manner. In this case, the first two altitudes were flown as planned, and then the drone was landed and the sensor apparatus and battery were switched before completing a second flight at the other two altitudes. For this reason, flight times were not simultaneous but occurred approximately 24 minutes apart. Small changes in temperatures may have occurred during the time taken to change out the sensor and battery, however, it is not believed that temperatures would have changed significantly enough during that time to impact results

5.3 Eco-Cities and Regional and Municipal Strategy Context

Ecocity Builders define cities as urban eco-systems, analogous in many ways to living, breathing organisms [34]. Cities are complex, dynamic, constantly changing entities that respond and adapt to their surroundings and the people, materials, and natural systems contained within them. The urban heat island phenomenon is the perfect example of how the complex interplay of energy and materials within a city can result in adverse consequences. Understanding and monitoring the material and energy inputs linked to UHIs is thus important to managing the health of our cities.

Ecocity Builders have created the International Ecocity Framework & Standards [35] to guide cities in taking a holistic approach to becoming sustainable urban organisms that can exist and thrive within the bounds of the planet. The framework includes 18 interconnected standards for municipalities to strive towards. Of these 18 standards, several have special relevance for UHI mitigation planning: (1) The standard for clean air, which deals with urban airflows and the movement of pollutants and GHGs; (2) the standard for green buildings, which encourages holistic, sustainable, and passive building strategies and considers the thermal impact of materials in cities; (3) the standard for healthy soils, which encourages a robust urban forest and ensures natural infiltration of rains and stormwater into the ground; and (4) the standard for access by proximity, which encourages pedestrian focused urban design that lends itself to increased vegetation, less impervious surfaces, and smaller, less sprawling cities. [35].

Features noted as significant in this study such as building materials, impervious surfaces, vegetation and trees, and building density, are major players in the above ecocity standards. When the relationships between these factors and urban heat are better understood, solutions can be identified. This study demonstrates that local-scale features likely play a role in the exacerbation or mitigation of urban heat in the atmosphere immediately above. When these microscale features are multiplied within a city, UHIs result. Therefore, understanding and correcting local features that are causing the exacerbation of heat on a broad scale is one potential pathway to reducing UHIs. And by extension, prioritizing ecocity standards in urban planning could achieve the same end.

A review of the City of Vancouver and Metro Vancouver's strategies and frameworks shows they are making significant steps towards identifying and addressing the issue of UHIs within the Ecocity framework. However, the strategies are lacking emphasis on the importance of building material selection, reduction of dark roofs, and green infrastructure such as green roofs and walls, which could further improve their strategies for managing urban heat.

6.0 Conclusion

The efforts of this study enabled the measurement and comparison of vertical air temperature profiles in downtown Vancouver for the first time. The study findings were able to corroborate the results of similar studies that analysed surface temperatures in urban landscapes, as well as identifying some new evidence. For example, results verified that high degrees of vegetation and tree canopy coverage such as urban parks have protective cooling effects, and that areas with greater degrees of impervious surfaces are warmer. Study results also supported theories about the impact of tall buildings on heat: specifically, that tall buildings insulate interior locations from normal cooling overnight, and that daytime surface temperatures in areas with greater urban canyons are cooler. However, this study also newly noted that the trapped air within urban canyons remains warm into the morning even at height, and that the daytime cooling effect noted at the surface of such locations does not extend into the air above. This warm column of air appeared to extend far up into the RSL, beyond the average building height.

Another finding of note is the possible significance of horizontal advection due to coastal sea breezes in heat distribution. One site studied, which was located next to several heat mitigating features such as a large green roof, a small urban park, and the ocean, was coolest in the morning but exhibited significant warming during the afternoon, against expectations. Dominant sea breeze directions in the region may have blown warm air from the adjacent downtown core over the site, dominating the heat mitigating features of the site. This also speaks to the importance of having UHI mitigation features integrated across the entire downtown, as isolated mitigation features are not impactful enough on their own.

In summary, an improved understanding of the impact of local features on both surface temperatures and the air temperatures above will better inform UHI mitigation strategies. Mitigation strategies must be applied at the local scale, as well as the municipal and regional scale, in order to have a meaningful impact on improving city health and resiliency to climate change. Further research to observe vertical temperature profiles in a wider variety of urban locations, away from areas influenced by the ocean, would be beneficial to better understand the impact of urban features on local atmospheric heat. The City of Vancouver and the Metro Vancouver region are working on addressing the issue of UHIs within the Ecocity framework. However, additional emphasis on the importance of building material selection, reduction of dark roofs, and more green infrastructure could further improve the robustness of their strategies for managing urban heat.

7.0 References

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