2015

Seasonal and Diurnal Patterns of Temperature Inversion Formation and Breakup in a Topographically Complex Urban Environment

Michael A. Allen

Brooke A. Holmes

Follow this and additional works at: http://pilotscholars.up.edu/env_studpubs

Part of the Environmental Sciences Commons

Seasonal and Diurnal Patterns of Temperature Inversion Formation and Breakup in a Topographically Complex Urban Environment.

Michael A. Allen and Brooke A. Holmes
Department of Environmental Studies
University of Portland
5000 N Willamette Blvd
Portland, Oregon 97203 USA

Faculty Advisor: Dr. Ted C. Eckmann

Abstract

Measuring air temperatures and winds at several heights in a dense urban area over a nine-month period reveals important seasonal differences in patterns of atmospheric stability, boundary-layer circulation, and other important factors that affect concentrations of air pollutants. The study site in Portland, Oregon includes natural topographic variations from 5 meters above sea level at the shore of a heavily industrialized stretch of the Willamette River, up to 50 meters above sea level atop a nearby bluff where residents often complain of poor air quality. This study installed, and continues to maintain, a network of remote automated weather stations ranging in altitude from river-level to the rooftops of buildings up to eight stories high, spanning a range of 70 m in the vertical from the lowest to highest station altitude, within an area of only 0.25 square km. Prior to this study, the density of weather observations in this area was often insufficient for resolving the conditions relevant to analyzing and monitoring air pollution events, but the significantly higher resolution of meteorological data now available for the area shows promise for addressing these issues. Station measurements include air temperatures and humidities at multiple heights per station, wind direction, wind speed, gust speed, solar radiation in multiple wavelength ranges, direct-diffuse ratios of solar radiation, air pressure, precipitation rates, leaf wetness, soil moisture, thermal-infrared radiant temperatures, kinetic temperatures, and boundary layer fluxes. This study also designed new tethersonde sampling methods to complement the ground-based stations with high-resolution data on vertical profiles of air temperatures, humidity, and winds within the boundary layer. Results show strong, low-level temperature inversions that are often more diurnally-constant in winter than in other seasons, with important implications for local air pollutant concentrations. Applications include improved understanding of local atmospheric patterns, which could help to inform better policies for addressing air quality issues.

Keywords: temperature inversion, air pollution, urban climate

1. Introduction

Urban areas located within valleys[1] and surrounded by significant topographic features[2] often experience significant air pollution problems[3]. These problems spur from a number of near-surface urban phenomena including the development of urban-boundary layer temperature inversions[4], reduced advection and ventilation out of the urban canopy, and significant anthropogenic heating. Urban features, including open and closed developments[5], building clusters, impervious and vegetated surfaces, and thermally active structures create significant local thermal complexity in urban areas, especially when combined with local topography. These factors exert a significant influence over diurnal and seasonal patterns of temperature inversion formation and breakup[6]. Urban and topographic features vary significantly from city to city and as such, study of the vertical temperature profile (VTP) within the urban canopy of a city tends to be extremely site specific, even between sites in a single urban area. Diurnal and seasonal patterns

within the vertical temperature profile of an urban area can also deviate significantly from established patterns[7] of boundary-layer temperature inversion formation and breakup[8]. Therefore, study of the vertical temperature profile in individual urban areas is paramount to characterize local air pollution problems resulting from near-surface temperature inversions, and also to gain a better understanding of how urban and topographic complexity influence temperature patterns within the urban boundary layer more generally.

In this study we define a temperature inversion as a layer of air within the vertical temperature profile wherein temperature increases along with an increase in altitude. In other words, a temperature inversion is defined as a layer of air within which the vertical temperature gradient is positive[7]. Boundary layer temperature inversion formation and breakup is driven largely by surface heating and wind dynamics resulting from patterns of surface heating/cooling. Urban features, by modifying rates of surface heating and cooling and directly influencing local area winds, have a significant influence on the development of inversion layers within the urban boundary layer. Local urban air quality can suffer as a result of temperature inversion forced limits on pollutant ventilation and advection.

As described by Whiteman 1981 and Whiteman & McKee 1982, temperature inversion formation in valley sites generally occurs during the nighttime hours as a result of increased air temperature cooling rates near the surface – thus the vertical temperature gradient is positive extending upward from the surface. Beginning after sunrise, breakup of the temperature inversion (BTI) then follows one of three patterns. Pattern one has the inversion broken by the growth of the convective boundary layer (CBL) from the ground up. Pattern two has the inversion broken from the descent of the inversion top as air temperatures within the valley inversion layer increase uniformly throughout the daytime. Pattern three observes a combination of both the aforementioned patterns with BTI occurring from both the growth of the CBL from the ground up and the descent of the inversion top. BTI generally begins shortly after sunrise and takes approximately 3.5 to five hours to complete regardless of pattern observed – although pattern three appears to be the most common[7].

Local topography and urban features have been shown to exert significant influence over formation[9] and breakup of boundary layer temperature inversions[2] and the structure of the vertical temperature profile in the urban boundary layer in general[10]. BTI pattern and time of destruction also vary seasonally, especially in higher latitudes with more extreme variations in solar angles and in regions prone to extended snow-cover. This study – ongoing and expanding as of 2015 – examines the influence of complex local topography and urban features on the formation and breakup of temperature inversions within the urban boundary layer in order to better characterize local air pollution events.

2. Study Site Characteristics and Experimental Design/Instrumentation

Our study site is located in Portland, Oregon USA. Land use and urban features in the study site and the surrounding area are characterized by two distinct urban zones. The first is a large industrial park, locally known as "Swan Island". Surface coverage in this area is characterized by widespread industrial buildings and impervious surfaces in close proximity to the Willamette River, as shown in Figure 1. The second zone is a heavily populated residential neighborhood and university campus located on a bluff approximately 50m above Swan Island and the Willamette River. Land coverage in the bluff zone is more variable but in general has a higher percent coverage of ground vegetation, tree cover, and pervious surfaces punctuated by single-family homes, and the University of Portland campus.

The edge of the fifty meter bluff bisecting the two urban zones is visible as a line of trees wrapping under the University campus and surrounding neighborhood. Areas below the bluff line are termed "urban zone 1"; areas above the bluff line are termed "urban zone 2". Figure 2 shows the locations of automated weather stations installed for this study, along with their elevations. Topographic contours in Figure 2 show the bluff as a steep physical boundary between the two urban zones and their distinct elevations.

In order to characterize the local microclimate and vertical temperature profile in the study area, five remote automated weather stations were installed at multiple heights spanning seventy meters in the vertical over a horizontal area of only 0.25 km^2. The Mehling, Shiley, and Christie stations are installed on building rooftops in the University campus. The Swindells station is installed at bluff level near the bluff line. The Pier C station is installed on a pier extending out into the Willamette River off Swan Island and is situated just above the river level.

Station measurements included air temperatures and humidities at multiple heights per station, wind speed, wind direction, wind gusts, incoming solar radiation in several spectral ranges, direct-diffuse ratios of incoming radiation, precipitation, air pressure, leaf wetness, soil moisture, thermal-infrared radiant temperatures, surface kinetic temperatures, boundary layer fluxes, and photovoltaic performance. The Mehling, Shiley, and Christie stations use Onset U-30 data loggers set to five minute recording intervals. The Swindells and Pier C stations use APRS Revision G data loggers and record measurements on a single minute interval. Data from both station and logging types are

assimilated onto a five minute interval and missing data is omitted from the entire dataset in order to maintain validity and consistency between stations and between analyzed time periods.

Figure 1. Aerial photo of the study site (courtesy of Google Images). The two urban zones and the weather stations installed by this study are labeled. Note the line of trees at the edge of the bluff delineating the boundary between the two urban zone.
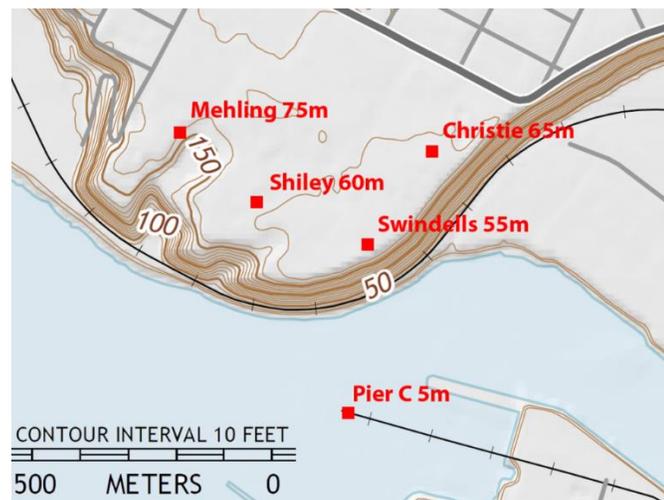

Figure 2. Topographic map (courtesy of USGS) with the locations of weather stations used in this study, and the ground altitude at the base of each station, in meters. Map contours in ten foot intervals. Note the sheer edge to the bluff creating a boundary between above-bluff and below-bluff zones as well as the vertical proximity of the industrial area to the adjacent Willamette River.

3. Results

The following sections detail patterns of temperature inversion formation and breakup during the daytime over two representative months for Portland Oregon summer and winter seasons (September 2014 and January 2015 respectively). Patterns are represented using vertical temperature profiles informed by observed data taken at the indicated time each day averaged over the entire month-long period (Figures 3 through 6). In other words, each line in these four figures is constructed using temperatures recorded daily at the indicated time averaged over the entire

representative month. This procedure is used to construct lines representing the vertical temperature profile on and below the bluff for several hours during the warming and cooling portions of the day. Vertical temperature profiles extend from river level (at the Pier C station), to bluff level (at the Swindells station), and eventually to approximately twenty five meters above bluff level (at the Mehling station).

3.1. Summertime vertical temperature profile analysis

The following two sections and their figures detail two distinct and opposite diurnal patterns of temperature inversion formation and breakup bisected by the bluff line averaged over a representative summertime month. Patterns of summertime BTI indicate significant stratification both in terms of vertical temperature profiles and stability on and below the bluff line.

3.1.1. summertime warming period stable layer stratification

Figure 3 shows vertical temperature profile development for the morning/early afternoon warming period means for the entire month of September 2014. Summertime patterns of stable layer development over the month-long sample differ significantly when examined above and below the bluff.

   Below the bluff (between the river level "Pier C" station and the bluff level "Swindells" station) a positive vertical temperature gradient exists through the late morning hours. As the morning and early afternoon diurnal warming period progresses, the temperature inversion below the bluff weakens significantly. Month-long averages for September indicate complete breakup of this temperature inversion below the bluff level by approximately 23:00 UTC (4:00pm local time, not shown).

   Above the bluff, the vertical temperature gradient at 19:00 UTC (noon local time) shows a weak temperature inversion (when examined from the Swindells station to the Mehling station). As the diurnal warming period progresses, the temperature inversion in the ten meters immediately above the bluff (between the "Swindells" and "Christie" stations) strengthens significantly through the late morning and early afternoon hours. Above the bluff, the temperature inversion reaches a maximum strength at approximately 22:00 UTC (3:00pm local time).
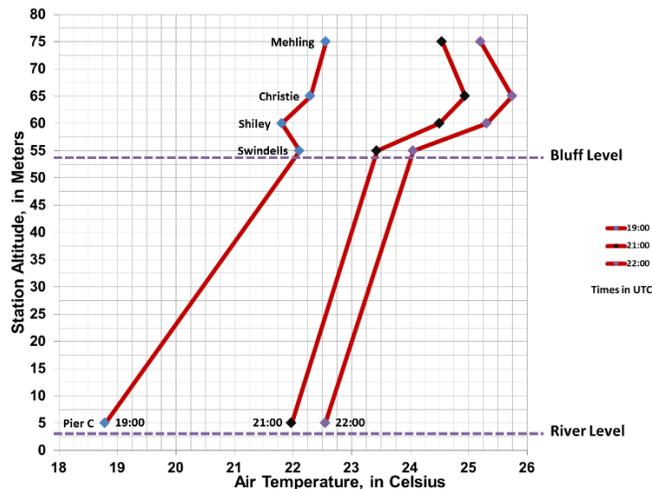

Figure 3. Diurnal warming period vertical temperature profile lines at 19:00, 21:00, and 22:00 UTC (noon, 2:00pm, and 3:00pm local time, respectively) using temperatures recorded daily at the indicated time averaged over the month of September 2014. Bluff and river levels are labeled as dashed lines.

3.1.2. summertime cooling period stable layer stratification

Figure 4 shows vertical temperature profile development for the late afternoon/evening diurnal cooling period averaged over the month of September 2014. By 0:00 UTC (5:00pm local time) BTI below the bluff is complete, yielding a layer with approximately neutral stability that extends upwards from river level to bluff level.

Above the bluff, at approximately the same time (0:00 UTC, 5:00pm local time) the positive vertical temperature gradient is at its maximum strength. This time when the temperature inversion above the bluff reaches its maximum strength also marks the time in which stratification between the two air masses bisected by the bluff line also reaches its maximum, as the positive vertical temperature gradient above the bluff coincides with complete BTI below the bluff. BTI above the bluff then occurs overnight.

Below the bluff, after BTI is complete, the inversion begins to build again as the temperature across the bluff continues to cool into the late evening hours. The stability of this layer continues to strengthen over the nighttime hours. Above the bluff, in contrast, after the layer reaches its time of maximum stability, the inversion begins to dissipate as diurnal cooling progresses into the late evening hours. This again highlights the contrasting patterns of temperature inversion formation and breakup above and below the bluff line.
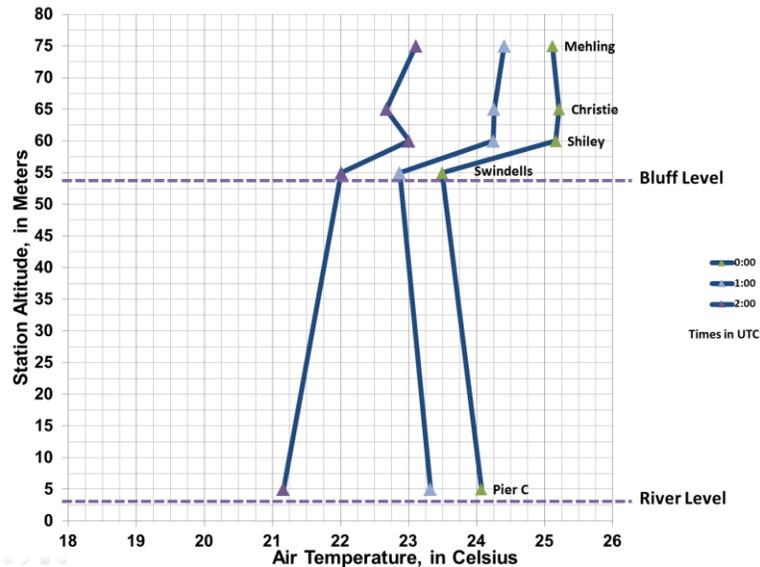

Figure 4. Daytime cooling period vertical temperature profile lines at 0:00, 1:00, and 2:00 UTC (6:00pm, 7:00pm, and 8:00pm local time, respectively) using temperatures recorded daily at the indicated time averaged over the month of September 2014. Bluff and river levels are labeled as dashed lines.

3.2. Wintertime vertical temperature profile analysis

The following two sections and their figures detail diurnal patterns of temperature inversion formation and breakup bisected by the bluff line averaged over a representative wintertime month. Wintertime vertical temperature profiles averaged over this month show decreased stratification above and below the bluff, and reduced stability, as compared to the preceding example from September.

3.2.1. wintertime warming period stable layer consistency

Figure 5 shows vertical temperature profile development for the morning/early afternoon warming period averaged over the month of January 2015. The layer below the bluff remains stable through the warming period hours with only slight weakening before 19:00 UTC (noon local time). Above the bluff an approximately isothermal layer persists into the late morning hours. As the bluff warms, a weak temperature inversion layer begins to form between 19:00 and 21:00 UTC (11:00am and 1:00pm local time, respectively). This inversion layer above the bluff persists at approximately the same strength into the afternoon/evening cooling period of the day.
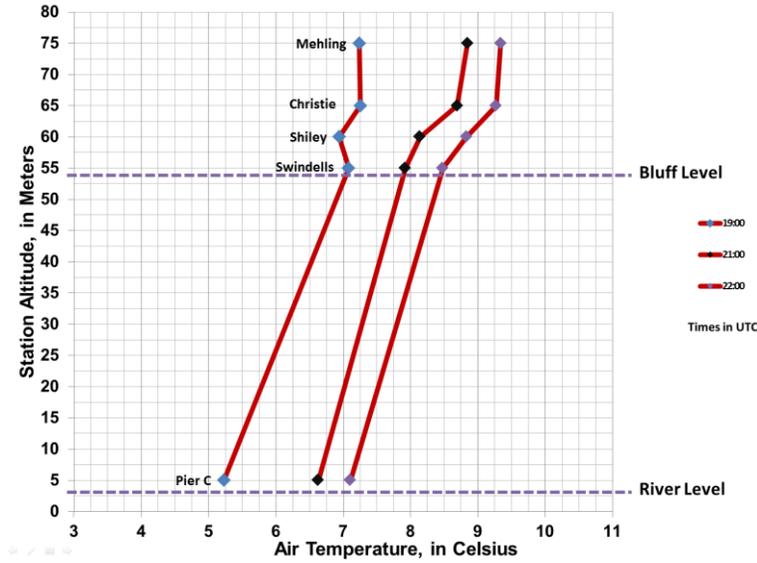
Figure 5. Daytime warming period vertical temperature profile lines at 19:00, 21:00, and 22:00 UTC (11:00am, 1:00pm, and 2:00pm local time, respectively) using temperatures recorded daily at the indicated time averaged over the month of January 2015. Bluff and river levels are labeled as dashed lines.

3.2.2. wintertime cooling period stable layer consistency

Figure 6 shows vertical temperature profile development for the late afternoon/evening cooling period averaged over the month of January 2015. Below the bluff, the vertical temperature gradient remains positive through the evening cooling period and into the nighttime. Month-long analyses of the wintertime temperature inversion below the bluff show that the stable layer remains diurnally constant. Wintertime BTI below the bluff only occurs under major synoptic fluctuations or significant shifts in boundary-layer wind direction or speed.

Above the bluff, the stable layer persists through the late-afternoon and evening hours, albeit slightly weaker than summertime inversion patterns. The time of maximum stability for this layer is more variable over the winter than in the summer, occurring between approximately 22:00 and 0:00 UTC (2:00pm and 4:00pm local time, respectively). BTI above the bluff occurs overnight, similar to the summertime analyses.
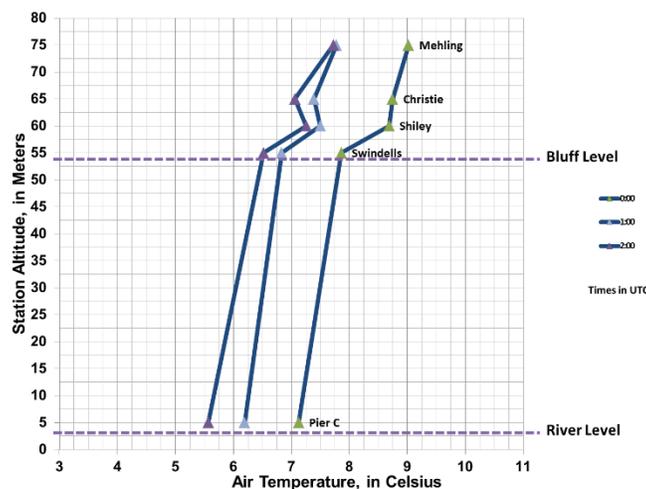

Figure 6. Daytime cooling period vertical temperature profile lines at 0:00, 1:00, and 2:00 UTC (4:00pm, 5:00pm, and 6:00pm local time, respectively) using temperatures recorded daily at the indicated times averaged over the month of January 2015. Bluff and river levels are labeled as dashed lines.

435

4. Discussion of Vertical Temperature Profile Analysis

The following sections provide an analysis of stratified patterns of temperature inversion formation and breakup observed above and below the bluff in our study as well as our proposed explanation for the same. In addition, we address seasonal variations in diurnal stable layer development between our two study periods.

4.1. Analysis of two stratified patterns of temperature inversion formation and breakup

Results from summertime VTP analysis show two distinct patterns of temperature inversion formation and breakup bisected vertically by the bluff line. Below the bluff, daytime BTI and nighttime stable layer formation follows patterns outlined in section one, as well as extensively in the literature (see Kanda 2007[10] and Arnfield 2002[11] for extensive reviews of urban climate research). A stable layer forms over the nighttime hours, following conduction between the cooling ground (and water) surfaces and the adjacent air. The same pattern in reverse follows the daytime warming period as conduction between adjacent air and the warming ground surfaces forces BTI below the bluff. BTI below the bluff is completed over the late afternoon/evening hours. To summarize, BTI below the bluff is forced largely during the warming hours of the daytime, while stable layer formation occurs during the cooling period and nighttime hours.

In the air mass above the bluff, stable layer formation and BTI follows a distinctly opposite pattern. A layer with approximately neutral stability persists into the morning hours. A temperature inversion forms and intensifies during the warming period of the day (late morning through early afternoon) reaching a maximum at approximately 5pm local time. The inversion dissipates slowly over the cooling period of the day with BTI occurring overnight. To summarize, BTI above the bluff is forced largely over the nighttime hours, while stable layer formation occurs during the warming period hours. The temperature inversion in the layer just above the bluff reaches its maximum strength at approximately 0:00 UTC (5:00pm local time). Of particular note is the coincidence of the inversion maximum above the bluff and BTI completion below the bluff, both occurring in the evening hours.

4.2. Proposed explanation for daytime stable layer formation along the bluff line

Our proposed explanation for the daytime stable layer formation and intensification above the bluff is as follows. Two stratified air masses develop, bisected vertically by the bluff line. These two air masses differ in their daytime heating rates and nighttime cooling rates. Daytime convergence of the two air masses at the bluff line boundary (both vertically and horizontally) becomes the setup for the daytime formation of strong temperature inversions along the bluff line.

The air mass on and above the bluff (over urban zone two) is subject to daytime intensification from increased surface heating of urban features, impervious surfaces, and the direct anthropogenic heat input. Conduction of air adjacent to the surface and subsequent convection into the air layer over the bluff intensifies both the daytime heating rate and the nighttime cooling rate of the air mass above the bluff. Air below the bluff (over urban zone one) has its heating and cooling rates retarded by its close proximity to the Willamette river. Thus, the overall daytime and nighttime temperature extremes are intensified above the bluff and reduced below the bluff.

We conjecture that daytime stable layer formation above the bluff is not a result of boundary layer heating of the air mass, but rather orographic lifting of cooler air from the air layer below the bluff. Analysis of wind direction patterns above and below the bluff show winds from the SSE to ESE over both the summer and winter months (wind flow towards the bluff). Wind from below the bluff horizontally towards the bluff forces orographic lifting of cooler, river-influenced air into the lower layers of the air mass on the bluff, thus creating a significant positive vertical temperature gradient in the lowest layers of the air mass above the bluff. The significantly reduced cooling rate of the air layer below the bluff coupled with sustained flows towards and up the bluff maintains and intensifies the stable layer on the bluff. This flow phenomenon persists even as the layer above the bluff is subjected to anthropogenically-forced intensified heating rates during the daytime warming period, as the warming air is constantly replaced by cooler, orographically-lifted air from below the bluff during the daytime.

4.3. Seasonal variations in diurnal VTP patterns above and below the bluff.

The previous two sections cover in detail summertime patterns of temperature inversion formation and breakup. Summertime analysis shows significant stratification between patterns above and below the bluff. Our wintertime analysis shows that this diurnal pattern of stratification across the bluff line is not as strong over the winter months.

Analysis of the VTP over the month of January 2015 (a representative wintertime month for Portland, Oregon) shows that diurnal patterns of stable layer development and BTI are not as pronounced compared to summertime analysis. Below the bluff, an inversion layer is consistently present, with BTI only occurring under exceptional circumstances like major synoptic changes. Above the bluff, stable layer formation and BTI follows similar patterns outlined in the summertime analysis albeit with significantly less intensity. BTI occurs over the nighttime hours, with an approximately isothermal layer carrying over into the morning. The formation of an inversion layer above the bluff follows the daytime warming period. The positive vertical temperature gradient above the bluff reaches a maximum at approximately the same time as indicated by our summertime analysis. The reduction in stable layer intensity is likely a result of reduced overall insolation during the daytime – a product of shorter daytime length and a more acute solar angle.

5. Implications for Local Air Pollution Dispersion

The development of boundary-layer temperature inversions significantly reduces the ventilation of air pollution contained within[12] or under[2] the stable layer. We posit that the structure and diurnal patterns of the bluff's vertical temperature profiles play a significant part in local nuisance odor and air quality problems. The formation of a daytime temperature inversion in the layer just above the bluff, owing to the orographic transport of cool air from below the bluff, coupled with BTI below the bluff in the late afternoon hours fosters the dispersion of pollutants within the unstable air mass extending from river level to just above the bluff level.

Late afternoon and evening stable layer formation, particularly when strongest in the layer immediately above bluff level, poses a significant human health risk to the highly-populated residential neighborhood and University campus at the bluff level. Air pollutants emitted from Swan Island throughout the day build up within the persistent stable layer below the bluff. Vertical mixing following from BTI below the bluff in the late afternoon allows for the vertical dispersion of air pollution onto the bluff. Under a less stable vertical temperature profile, these pollutants would continue upwards past the bluff level. However, given the formation of a stable layer in the lowest layers above the bluff, those pollutants tend to stagnate frequently at or near bluff level. We suspect that this inhibition of vertical mixing in the five to ten meters above bluff level plays a major role in explaining why the area's residents complain frequently of air pollution problems.

6. Conclusion

Our study found significant deviations from typical patterns of temperature inversion formation and breakup found in urban climate and meteorological literature. We believe these deviations are the result of the formation and convergence of two stratified air layers forced by a complex urban and topographic environment. The daytime convergence of these two air layers would explain the observed formation of strong, boundary-layer inversions as pockets of air cooled by the nearby river are orographically lifted into warmer urban air above. Stagnation of air pollutants within the boundary-layer temperature inversion is likely to follow as BTI below the bluff level progresses into the late afternoon and evening hours.

This study highlights the necessity of local area study of the vertical temperature profile, particularly in areas of significant urban and topographic complexity. Our analysis shows that urban and topographic complexity can lead to novel patterns of stable layer development and BTI within the urban boundary layer. Further study of stability in the urban boundary layer can be used to better inform urban planning and industrial operations schedules to reduce air pollutant concentrations within urban areas.

7. Acknowledgements

8. References

1 Beard, JD., C. Beck, R. Graham, S. Packham, M. Traphaganm R. Giles, and J. Morgan, Winter temperature inversions and emergency department visits for asthma in Salt Lake County, Utah, 2003-2008. *Environ. Health Perspect.*, **120**:1385-1390, doi: 10.1289/ehp.1104349.

2 Rendón, A., J. Salazar, C. Palacio, V. Wirth, and B. Brötz, 2014: Effects of Urbanization on the Temperature Inversion Breakup in a Mountain Valley with Implications for Air Quality. *J. Appl. Meteor. Climatol.*, **53**, 840–858. doi: http://dx.doi.org/10.1175/JAMC-D-13-0165.1

3 Malek, E., T. Davis, R. Martin, P. Silva, 2005: Meteorological and environmental aspects of one of the worst national air pollution episodes (January, 2004) in Logan, Cache Valley, Utah, USA. *J. Atmos. Res.,* **79.** 108-122, doi:10.1016/j.atmosres.2005.05.003.

4 Nakamura, Y. and T. R. Oke, 1988: Wind, Temperature, and Stability Conditions in an East-West Oriented Canyon. *Atmos. Environ.* **22**, 2691-2700, doi:10.1016/0004-6981(88)90437-4.

5 Stewart, I. and T. R. Oke, 2012: Local Climate Zones for Urban Temperature Studies. *Bull. Amer. Meteor. Soc.*, **93**, 1879–1900. doi: http://dx.doi.org/10.1175/BAMS-D-11-00019.1

6 Kanda, M., R. Moriwaki, and Y. Kimoto, 2005: Temperature Profiles Within and Above an Urban Canopy. *Boundary-Layer Meteorology*, **115**, 499-506, doi: 10.1007/s10546-004-5644-5.

7 Whiteman, D., 1981: Breakup of temperature inversions in deep mountain valleys: Part I. Observations. *J. Appl.Meteor.*, **21**, 270–289.

8 Whiteman, D. and T. McKee, 1982: Breakup of Temperature Inversions in Deep Mountain Valleys: Part II. Thermodynamic Model. *J. Appl. Meteor.*, **21**, 290–302. doi: http://dx.doi.org/10.1175/1520-0450(1982)021<0290:BOTIID>2.0.CO;2

9 Masson, V., 2006: Urban surface modeling and the mesoscale impact of cities. *Theor. Appl. Climatol.*, **84**. 35-454, doi:10.1007/s00704-005-0142-3.

10 Kanda, M., 2007: Progress in urban meteorology: A review. *J. Meteor. Soc. Japan*, **85B**, 363–383, doi:10.2151/jmsj.85B.363.

11 Arnfield, A. J., 2003: Two decades of urban climate research: a review of turbulence, exchanges of energy and water, and the urban heat island. *Int. J. Climatol.*, **23**: 1–26, doi: 10.1002/joc.859.

12 Janhäll, S., K. Olofson, P. Andersson, J. Pettersson, and M. Hallquist, 2006: Evolution of the urban aerosol during winter temperature inversion episodes. *Atmos. Environ.*, **40**, 5355-5366, doi: 10.1016/j.atmosenv.2006.04.051.