

Episodic Ozone Pollution in the Lower Fraser Valley, BC: A Tale of Three Episodes

By
Nadya Moisseeva

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Douw Steyn, Supervisor

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Abstract

The spatiotemporal characteristics of episodic ozone pollution in the Lower Fraser Valley of British Columbia have changed markedly over the past two decades. These changes are documented by Ainslie and Steyn (2007), who hypothesize that they have come about because of reductions in ozone precursor emissions strength, driven by aggressive air quality management plans.

This study sheds further light on this phenomenon by a parallel spatiotemporal analysis of three notable episodes, one in 1988, one in 1998 and one in 2009. These three episodes span the emissions reductions initiatives, and the analysis is designed to cast light on potential for future air quality management strategies. The analysis is based on a combined air quality and meteorological definition of an ozone episode. This paper investigates the particular meteorological conditions during each of these episodes, and shows that the most recent episode is characterized by record high temperatures, and suppression of the mixed layer, distinct from other episodes. In spite of reduced total emissions, the unusual meteorological conditions provide a context in which ozone pollution can still exceed applicable standards. The paper speculates on the implications for ozone pollution episodes in changed climates.

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1. INTRODUCTION

1.2 Lower Fraser Valley

Lower Fraser Valley (LVF) region of British Columbia is located at 49N on Canada/USA border. This approximately triangular valley is bounded by the Strait of Georgia on the west and confined by Coast Mountain Ranges in the north and Cascade Ranges in the south. Metro Vancouver (MV) with a total population of approximately 2.1 million is contained within LVF. Operated by MV lies a network of 26 air quality monitoring stations within the region from Horseshoe Bay in West Vancouver to Hope. Pollutants monitored by the network include both gases and particulate matter (2007 Lower Fraser Valley Air Quality Report, 2008). Ozone pollution specifically has been monitored since 1973. For the purpose of this study two stations were selected: YVR and YXX (refer to Figure 1).

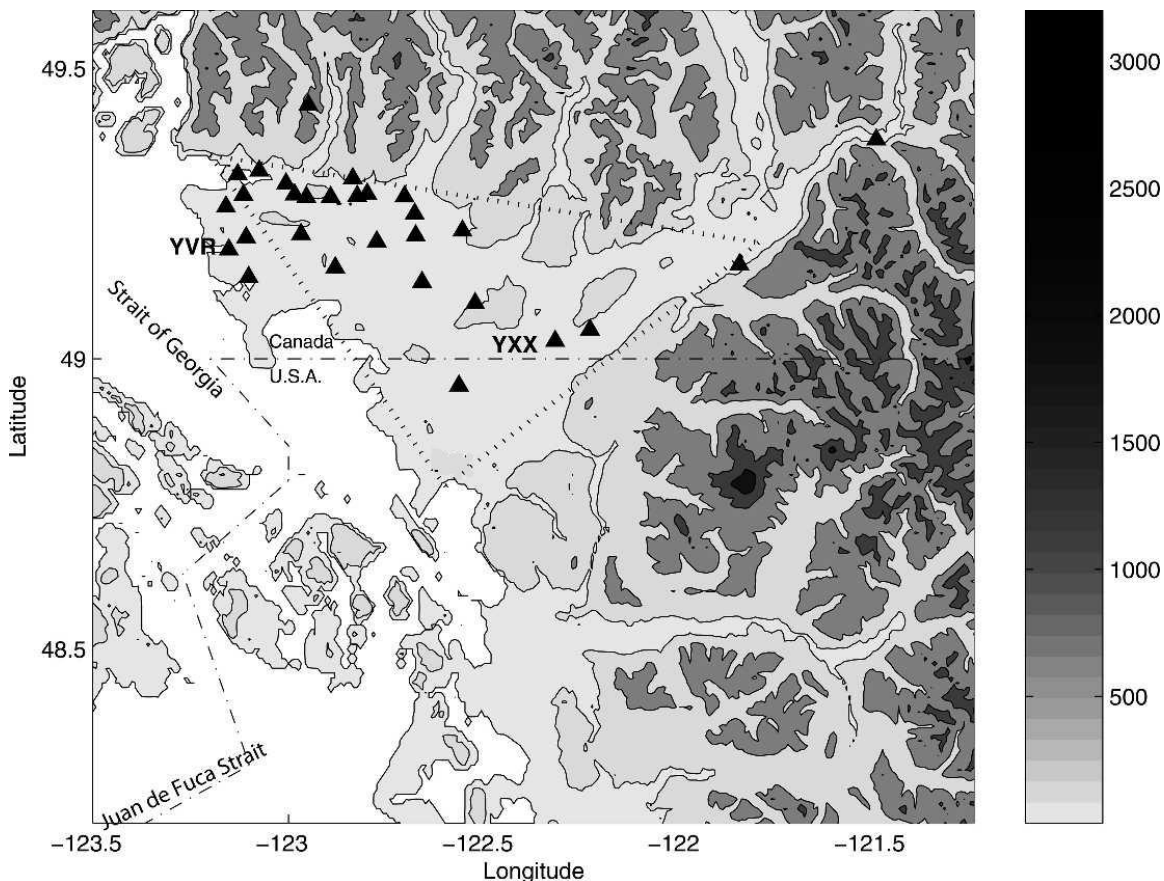


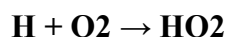
Figure 1. Topographic relief of LVF (m). Ozone monitoring station locations are shown in black. Selected stations at Vancouver International Airport (YVR) and Abbotsford Airport (YXX) are shown. The triangular shape of the valley is highlighted with dashed line. Source: Ainslie and Steyn 2007.

According to Steyn and Faulkner (1986) the observations from these two stations are sufficient for identification of mesoscale regimes. Both have unobstructed near-field fetches and are set in isolation from local topographic features. Moreover, they allow to capture the coastal/inland variability of conditions in the valley.

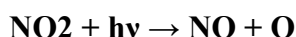
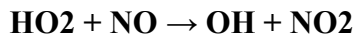
1.2 Ground Level Ozone Pollution

Tropospheric ozone pollution is a result of numerous chemical, physical, meteorological, anthropogenic and biogenic factors. Ground level ozone is a harmful pollutant that can be a threat to both human health and vegetation (Mulholland *et al*, 1998). The complexity of any spatiotemporal analysis of this pollution lies in the fact that the pollution is not a result of direct emission but rather an outcome of multiple photochemical reactions of the mixture of volatile organic compounds (VOCs) and oxides of nitrogen (NO_x). The process is accelerated in the presence of abundant sunlight and high temperatures (Oke, 1987).

The chemical reactions involved in tropospheric ozone formation are a series of complex cycles in which VOCs are oxidized to water vapor and carbon dioxide (Committee on Tropospheric Ozone, 1993). Oxidation begins with the reaction of a VOC with the hydroxyl radical. The hydrogen rapidly reacts with oxygen to give a peroxy radical HO₂.



Peroxy radicals then react with NO to give NO₂ which in the presence of light gives atomic oxygen and through reaction with oxygen a molecule of ozone:



The emission densities of these precursor substances are closely linked to human population in LFV (Steyn *et al*, 1999), majority of which is attributed to mobile sources, such as light-duty motor vehicles.

1.2 Three Episodes

Episodes, which are intervals of unusually high concentration of ozone generally occur in the summertime, have shown to become less severe since 1980s in LFV, despite a nearly doubled population size in the region (Ainslie and Steyn, 2007). This trend is attributed to the efforts and

significant reductions in precursor emissions through MV Air Quality Management Plans in 1994 and 2005. Working with local, provincial and federal agencies reduction programs were developed, that imposed standards for commercial, industrial and residential operations through a system of permits and regulations (2007 Lower Fraser Valley Air Quality Report, 2008). Metro Vancouver staff monitor permitted and regulated emission sources, and enforce air emission limits.

The ozone episode of 1988 which occurred in the beginning of September was well documented by Steyn *et al*, 1999. Anticyclonic weather, with high temperatures and suppressed mixed layer depth created ideal conditions for formation of ozone. Similarly, the summer of 1998 had notably hot and dry weather, which produced poor air quality in LFV in the end of July. The movement of ozone plume has shown to shift eastwards, due to rapidly growing populations of satellite cities around Vancouver that are generally located in south-eastern side of the valley (Joe *et al*, 1996). The 2009 episode, which has similarly occurred at the end of July, was also marked by record high temperatures and, moreover, a notable failure of the sea breeze circulation.

These three episodes span the emissions reductions initiatives, and thus the analysis is designed to cast light on potential for future air quality management strategies. The purpose of this study is to investigate the particular meteorological conditions, emissions, and ambient ozone concentrations during each of these episodes in parallel. The aim is to understand the contributing factors within each of the episodes and speculate on the future implications for ozone pollution in LVF.

2. DESCRIPTION OF DATA

2.1 Ozone Data

Hourly ambient ground level ozone measurements at YVR and YXX for the three episodes and days around them were obtained from BC Environment Air Quality (AQ) Index database. All AQ data was converted into standard unit of ppb and missing entries were filled using regular averaging.

2.2 Meteorological Data

2.2.1 Temperature

Mean hourly temperature data at YVR and YXX were obtained from BC Environment Air Quality Index database. Missing entries were filled in using regular averaging.

2.2.2 Pressure

Mean hourly pressures at YVR and YXX were obtained from Environment Canada online database. Data contained no missing entries.

2.2.3 Wind

Mean hourly wind speed (km/h) and direction (in 10 degrees from true North) at YVR and YXX were obtained from Environment Canada online database. Wind speed was converted to conventional units of m/s. It is also important to note, the low resolution on wind direction. The available data provides wind direction only in increments of 10 degrees. Scalar wind speed also appears to be collected using low sensitivity equipment as upon comparison with other sources, it proved unable to distinguish low wind speeds assigning “0” value to such instances. Unfortunately, higher resolution data was not available for all episodes. Therefore, for the purpose of consistency lower resolution data was used. These factors could have a particular effect on calculation of mixed layer depth (see section 2.2.4) as well as hodographs produced for each episode.

2.2.4 Mixed Layer Depth

Data for 1988 episode was obtained from acoustic sounder measurements, acquired from Steyn *et al* (1999). No acoustic sounder data was available for neither of the later episodes and thus the mixed layer depth was simulated using a model developed by Steyn (1980). Simulated data for 1998 was extracted from Steyn *et al* (1999). For 2009, the original model code in FORTRAN IV was converted to MATLAB and ran using appropriate input. Among others, the model requires sensible heat flux, mean wind speed and direction and temperature of the mixed layer as input. 2009 sensible heat flux was provided by Vancouver EPiCC. Mixed layer temperature was assumed to be equivalent to surface temperature. It is important to note, that the model assumes advection and is thus sensitive to input wind data. Considering the low resolution of wind data, the results provided by the model should be treated with caution.

2.3 Emissions Data

As part of Air Quality Monitoring Program MV releases Emissions Inventory every 5 years. The most current report (2007) provides estimated values for two primary pollutants associated with ozone

production: NO_x and VOC for years 1990, 1995 and 2000 as well as forecasted values for 2010. Intermediate values for years of interest were obtained using cubic interpolation of data. 1988 and 1989 values were estimated by interpolating backwards using 1990-1995 intervals. It is also important to note that values used for VOC exclude the biogenic component, due to it being not controllable and nearly constant in time.

3. ANALYSIS

In order to understand the dynamics of episodic pollution and the changes in its extent and spatiotemporal features it was necessary to examine factors responsible for the formation of an episode. Identification of an episode itself requires close examination of those factors, and inevitably involves a certain amount of subjectivity. For the purpose of this study, three components of episodic pollution were established. Firstly, identification of an anomaly in near-surface ozone concentration is essential. Therefore, the ambient ozone concentration was examined for each of the episodes and several days before and after their occurrence. Secondly, an analysis of ground level meteorological conditions is of primary importance to the understanding of sudden peaks in ozone concentration as factors such as temperature govern the chemical processes responsible for formation of ozone in the troposphere. Lastly, analysis of LFV Emissions Inventory is necessary to help identify possible changes in the emissions and their components throughout the past two decades.

3.1 Defining an Episode

One of the greatest challenges in the analysis of episodic pollution is the identification of the episode itself. The concentration of ozone in the troposphere is highly variable in both space and time. Not only is there a great change on diurnal basis, high variability is also evident amongst individual days and on a larger scale, amongst the seasons. Often the episode is defined based on a selected exceedence threshold (Vingarzan, and Taylor, 2003). For instance, all consecutive days that have surpassed the value of 82 ppb (Ainslie and Steyn, 2007) are considered to be part of an episode. For the purpose of this study, however, an alternative strategy was derived. Upon examination of both ozone concentration and meteorology a close link was established between temperature and ozone concentration. As evident from Figure 2 below, showing Temperature vs. Ozone scatter graph for YXX location, there is an obvious positive correlation between the two factors. The reason only

Abbotsford location data was used to establish this relationship, is because the meteorological conditions inland are independent from advection off the water. Due to variability amongst episodes no single trend line was added.

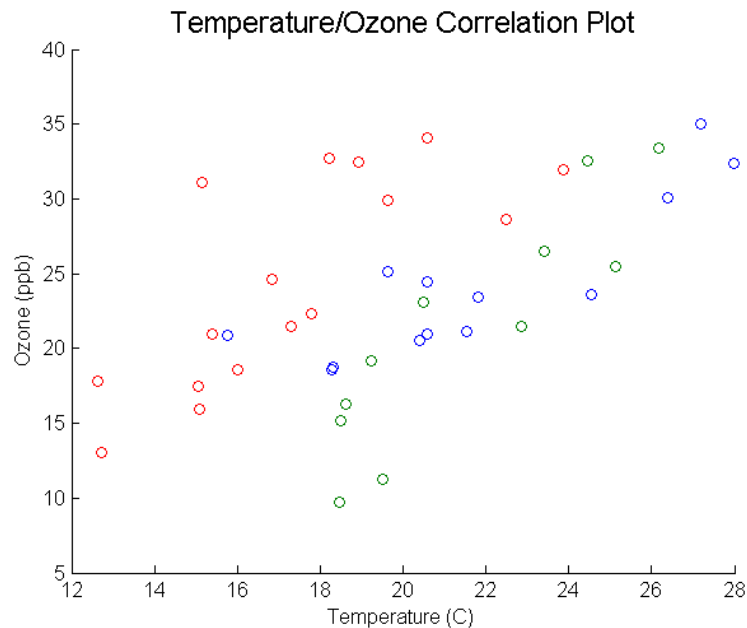


Figure 2. Correlation between temperature and ozone for three episodes: 2009 (blue), 1998 (green) and 1988 (red) at Abbotsford monitoring station. Ozone values are hourly means over the episode.

Therefore a definition of an episode was derived from both mean daily temperature and mean daily ozone concentration for combined YVR and YXX locations. Inevitably it requires visual analysis of both temperature and ozone data plotted on the same grid (refer to Figures A1-A3). Anomaly is identified based on both factors and marked on each figure. Note the varying scale for ozone concentration on the plots: due to change in severity of episodes over time, scale was fitted for best visualization. The following Table 1 summarizes the timing and duration of episodes for all three years.

Year	Day 1	Day 2	Day 3	Day 4	Day 5
1988	September 1	September 2	September 3	September 4	September 5
1998	July 26	July 27	July 28	July 29	-
2009	July 28	July 29	July 30	July 31	-

Table 1. Summary of timing and duration of 1988, 1998 and 2009 ozone episodes.

While this criterion appears to work well with the earlier episodes, the case of 2009 is not as clear cut. A sharp spike in ozone concentration emerges after a certain delay after the temperature rise

(refer to Figure A-1). Possible explanation for that could be the influence of sea breeze circulation, which feeds clean air to YVR location and lowers the apparent ozone values due to dilution. This issue will be examined in more depth in the following section.

3.2 Ambient Ozone Concentration

By examining time series plots of hourly ozone concentration (refer to Appendix E-1) for all three episodes one can see that the more recent cases of pollution were much less severe. 1988 episode has seen a record high O_3 of 212.5 ppb. The maxima of later episodes remain around 100 ppb. As mentioned earlier, such improvement can likely be attributed to air quality improvement efforts.

To compare the dynamics of each episode daily averages (mean over 24 hours) were examined (refer to Figures B-1-B-3). One of the commonalities is an approximately two day lag between the apparent onset of the episode between YVR and YXX. This feature could be attributed to the presence of sea breeze at the coastal location which induces circulation with clean off shore air mass. At the beginning of the episode there is still a reservoir of clean air in the Strait of Georgia. However, as the episode progresses and ozone is mixed into on-water air mass through reversed off shore winds, no more clean air is fed onto the coast resulting in the delayed rise in O_3 concentration.

Mean hourly ozone concentration provides an alternative view of episode dynamics. Timing of maximum ozone concentrations is easily interpretable from the plots (B-4-B-6). Note that the 2009 concentration appears to peak much earlier (~2pm) than in both of the earlier episodes (~5pm). This can likely be attributed to record high temperatures and lack of nightly cooling associated with the 2009 episode (see section 3.3.1 below).

Lastly, examining the trends over the span of 20 years is beneficial for our understanding of the dynamics of episodic pollution (refer to B-7-B-9). Comparing the spatial distribution of the ozone plume on the day of maximum concentration value shows the overall eastward shift, consistent with the findings of Ainslie and Steyn (2007). This can likely be explained by the expansion of MV and growth of its satellite cities. This growth is limited by water from the West, however, is unrestricted to the East. Urban growth results in increased emissions and thus a shift in pollution.

3.3 Meteorology

3.3.1 Temperature

As mentioned earlier, temperature is closely correlated with ambient ozone concentration in the troposphere.

Time series of ambient ground level air temperature can be found in Appendix E-2. The plots indicate an obvious diurnal variation and a consistent difference between the two selected locations, with Abbotsford Airport having a greater daily temperature variation for all episodes. The latter can be explained by the locations' different proximity to the ocean, and its known effect of temperature moderation.

However, for the purpose of comparison, it is more useful to examine both daily and hourly averages. Daily average plots (refer to C-1.1-C-1.3) provide a single mean value of ground level temperature for the day. There are evident common trends found in these plots. Standard deviation values are nearly double for YXX location as compared to YVR. This is not surprising as due to YXX being further away from the ocean shore, the moderating effects of water are felt to a lesser extent, thus producing greater diurnal variability. It is also worth noting that though both locations follow a closely related trend, YVR appears to have a slight lag. Once again it could be attributed to longer times required for heating of a near shore air plume due to thermal effects of water surfaces.

Hourly average trend for an episode provides a different sort of information. Plots of hourly temperature means for episode days only can be found in Appendix C (Figures C-1.4-C-1.6). 1988 and 1998 episodes both show greater temperature variation at YXX as compared to YVR. 2009 is marked by record high temperatures with lowest nightly values around 20C, as compared to other episodes where nightly mean temperatures were around 15C. The latter is likely to have a significant influence on the production of ozone. 2009 episode also shows a nearly identical trend between coastal and inland location suggesting failure of the sea breeze circulation.

3.3.2 Pressure

Surface pressure is one of the least variable components of the study. It has a rather indirect influence on the ozone concentration, as it is responsible for the transport of the plume. Pressure difference between various locations induces winds, therefore altering the spatial distribution of ground level ozone and either causing or preventing accumulation. Thus, hourly pressure *difference* rather than absolute values between YVR and YXX location was examined for each of the episodes. Averaging was done within the span of each episode (refer to Figure 3 below).

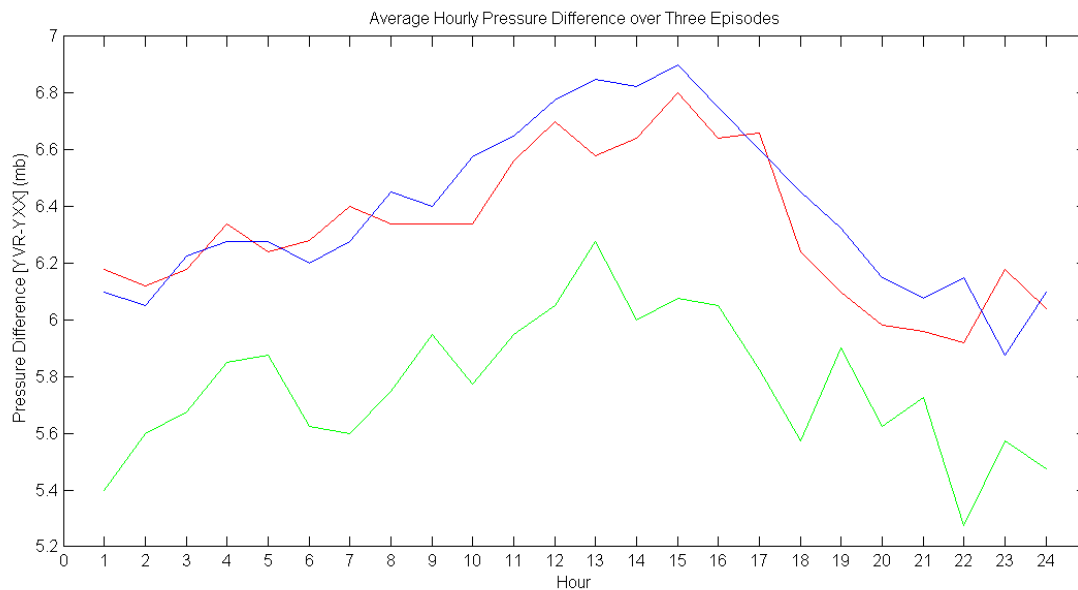


Figure 3. Average hourly pressure difference between YVR and YXX for 1988 (red), 1998 (green) and 2009 (blue) episodes. Dates included in averaging: September 1 –September 5 for 1988, July 26 – July 29 for 1998, and July 28– July 31 for 2009.

1988 and 2009 episodes appear to have a very similar pressure difference pattern suggesting similar wind dynamics in the two of the episodes. 1998 pressure differences follow similar trends but are notably lower, potentially resulting in lower westerly winds and reduced plume movement.

It is also important to note that all three episodes showed relatively high absolute pressure values indicating the presence of a high pressure system, commonly associated with episodic ozone pollution.

3.3.3 Wind

Wind dynamics directly determine whether ozone and the associated precursor species are transported downwind or contained locally. Lack of pressure gradient and therefore wind flow could result in accumulation of produced ozone and thus yield higher concentrations. In the summer time, LFV is dominated by westerly winds, as evident from wind-rose plots of wind direction at Abbotsford Airport for each of the episodes (Figures E-3.2, E-3.4, E-3.6). Coastal location inevitably falls under the strong influence of sea breeze circulation as evident from the binary distribution of wind directions on histograms in Figures E-3.1, E-3.3, and E-3.5

It is therefore meaningful to only consider westerly wind component for the analysis. Upon examination of hourly mean wind for each of the episodes (Figures C-2.1-C-2.3) several differences

become apparent. First of all, consistent with the pressure difference analysis one can see that 1998 episode was marked by suppressed winds (Figure C-2.2). Though 1988 (C-2.1) and 2009 (C-2.3) winds appear similar in magnitude, the latter can be singled out from other episodes as the sea breeze reversal is significantly delayed. 1988 and 1998 both show an onset of reversal taking place at YVR at around 8am, while 2009 wind reversal is delayed until noon. Likely, this can be described as the effect of abnormally high temperatures on local sea breeze circulation pattern. This is a particularly important consideration in the context of warming climate.

3.3.4 Cluster Analysis

Ainslie and Steyn (2007) have performed cluster analysis of wind measurements in LFV and have identified four mesoscale circulation regimes that are common to days of episode ozone pollution. According to Ainslie and Steyn the four regimes can be viewed as subclasses of two broad classes dependent on the morning wind direction at the coastal YVR station. Figure 4 below provides composite hodographs for YVR derived from cluster analysis.

Upon visual comparison of the four clusters below with hodographs produced for the three episodes at YVR (Figures C-3.1-C-3.3) one can conclude that all three seem to fit between cluster III and IV. These two regimes fall into a subclass governed by slack pressure gradients in the morning facilitating sea breeze circulation. Ainslie and Steyn also show that Cluster III is associated with earlier stages of ozone episode while cluster IV is the most common regime for last episode days.

The episodes selected for this study are known to be some of the most severe to occur in LFV over the past two decades. However, Ainslie and Steyn's frequency analysis suggests that regimes III and IV are *least* closely associated with ozone exceedence events (82ppb threshold). One could therefore speculate that the ozone pollution episodes occurring in regimes that are not typically associated with high ozone concentration increases their severity.

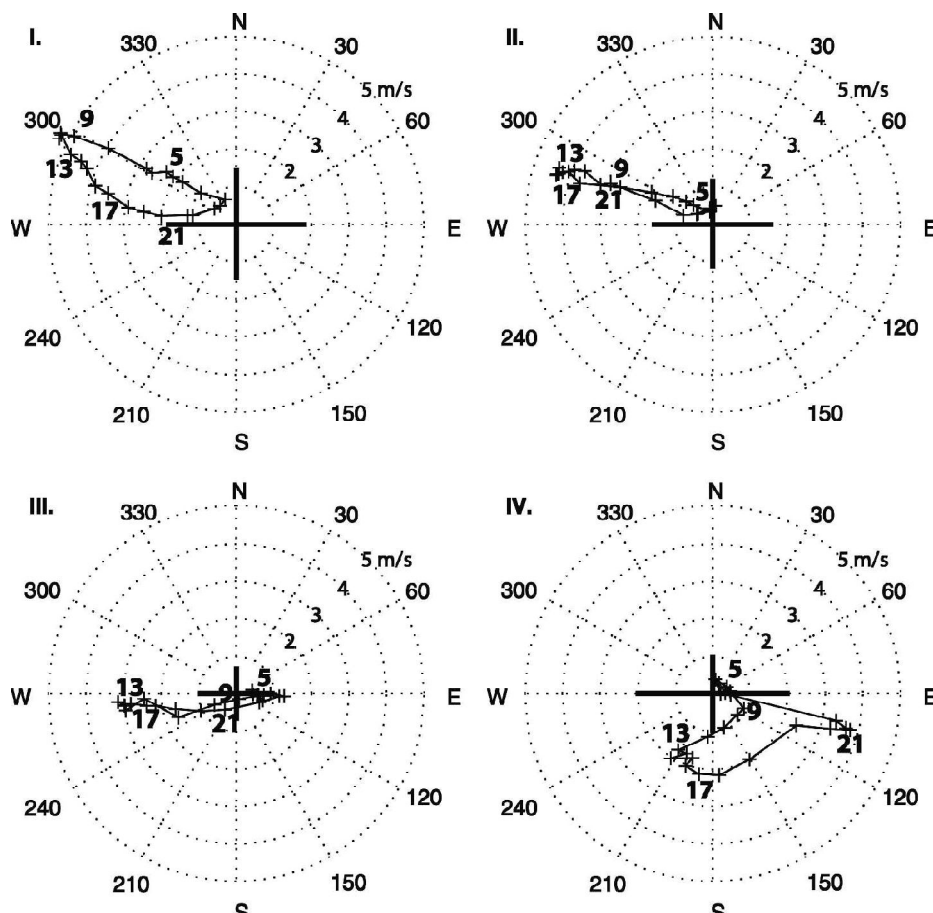


Figure 4. Composite YVR hodographs for clusters I, II, III and IV. The arms of the cross at the origin give the size of the average std dev of wind components. Boldface numbers indicate time (UTC). Source: Ainslie and Steyn (2007)

3.3.5 Mixed Layer Depth

Another important factor that influences the measured ground level ozone concentration is the mixed layer depth. The formation of ozone in the layers above the surface layer contributes to surface ozone concentration through rapid vertical turbulent diffusion within the mixing layer (Byun, 2007). Suppressed mixed layer is generally associated with higher ozone values as there is induced venting (McKendry, 1994).

Maximum mixed layer depth height for each three episodes was extracted from either acoustic soundings or mixed layer depth simulation model (see Section 2.2.4) and is summarized by Table 2 below. Model output can be found in Appendix E-4.

Episode	Maximum Mixed Layer Depth (m)
1988	670
1998	620
2009	470

Table 2. Maximum mixed layer depth associated with each episode.

The latest episode has a significantly more suppressed mixed layer, which is likely to result in higher surface level ozone concentrations. I.e. even given lower ozone production and accumulation as compared to earlier episodes, concentrations could remain high at ground level due to reduced amount of vertical mixing. It is, however, worth noting that the values for the earlier episodes are maximum height achieved amongst all episode days. For 2009, only average sensible heat flux data was available and, therefore, any extremes were likely lost. Never-the-less, the suppression is still evident as the variation of mixed layer depth between days does not usually vary by a large amount (Oke, 1987).

3.4 Emissions

Over the past two decades the Lower Fraser Valley has seen a tremendous improvement in ozone pollution. According to Ainslie and Steyn (2007) the positive changes can be attributed to two vigorous initiatives launched by Greater Vancouver Regional District in the form of two Air Quality Management Plans in 1994 and 2005. Ozone formation is driven by a complex non-linear photochemical relation between two directly emitted precursors: NO_x and VOC. The morning concentrations of VOCs and NO_x along with their differing rates of reaction with the -OH radical can greatly influence how much ozone is formed for a given site-day (Seinfeld and Pandis, 1998). It is important to note, that the amount of ozone produced is not simply dependent on the absolute concentration values of precursors, but rather on their relative amounts (Ying, 2009).

Interpolated data from the Lower Fraser Valley Emissions Report (2007) has been used to calculate VOC/NO_x ratios for years 1988-2010 (refer to Figure 5 below). There is an evident decline from 1.31 to 1.15 in the ratio in the years shown, which could be linked to the difference in severity of ozone pollution.

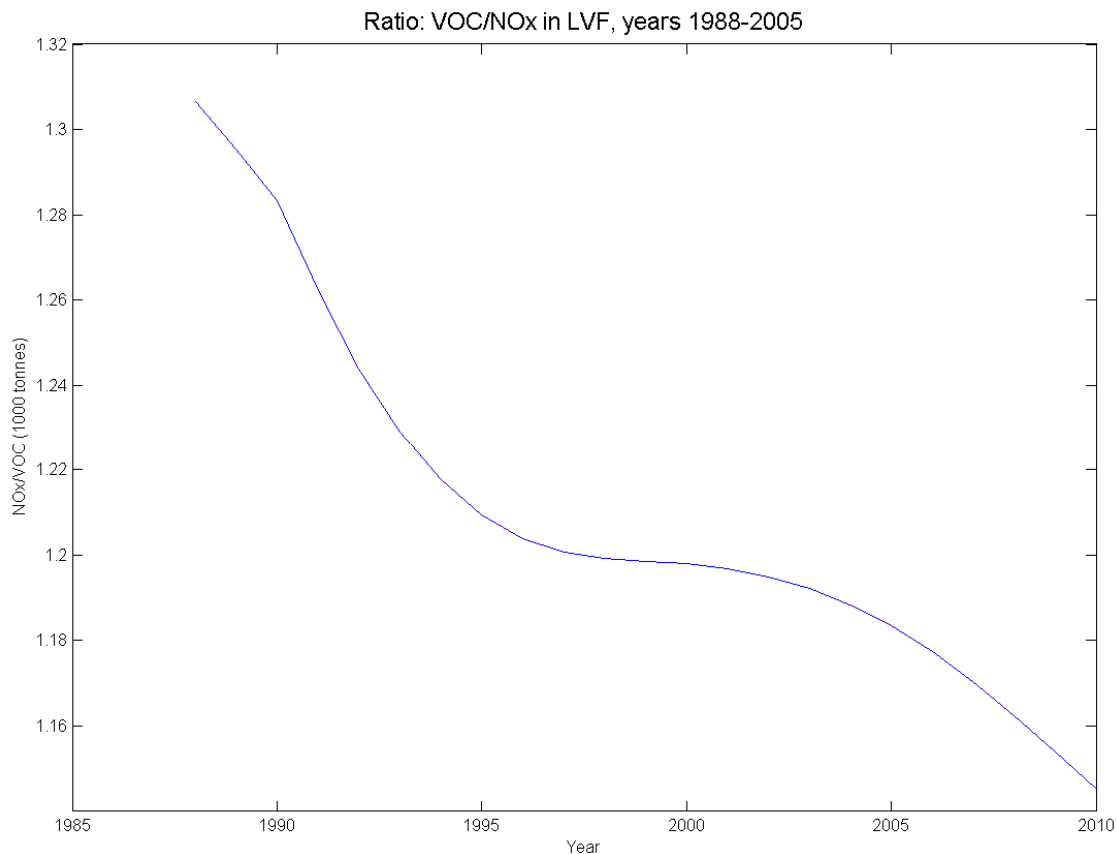


Figure 5. VOC/NOx ratio for years 1988-2010 based on LFV Emissions inventory.

It is important to note that ambient ratios often exceed by a substantial amount those calculated from emissions inventories (Committee on Tropospheric Ozone, 1992). Therefore, the absolute values of emissions should be treated with caution.

4. RESULTS AND CONCLUSIONS

Parallel spatiotemporal analysis of three notable ozone pollution episodes of 1988, 1998 and 2009 in the Lower Fraser Valley, B.C. was conducted. Each was examined on the basis of associated ambient ground level ozone concentrations, prevailing meteorological conditions and estimated precursor emissions. The overall severity of ozone pollution has seen a decrease over the past two decades as reflected by the episodes. It is, however, challenging to single out a factor responsible for the dynamics of a particular episode.

1988 episode was marked by extremely high ozone concentration values, while the meteorological conditions were favorable for suppression of ozone production. In comparison to other episodes, the 1988 episode had lower temperatures, greater mixed layer depth and moderate winds. Such conditions would generally lower pollutant concentrations. Therefore, the abnormally high O₃ values are likely to be the result of high emissions.

1998 episode has shown higher temperatures, but significantly smaller pressure gradient and thus lower winds. Episodic pollution could, therefore, have been a result of accumulation as well as abundance of heat and sunlight. Reduced emissions have contributed to overall lower O₃ concentrations.

2009 episode was marked by extremely high temperatures and lack of nightly cooling. Likely, due to these factors the sea breeze circulation pattern has been altered. Suppressed mixed layer depth further exacerbated ozone pollution, as less air volume was provided for vertical mixing. Though emissions have seen further reductions the severity of this episode was similar to that of 1998.

These findings have a number of unsettling implications. Considering the current warming climate, there is a potential of increase in severity of episodic ozone pollution regardless of the success of emission reduction efforts.

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APPENDIX A. Defining an Episode

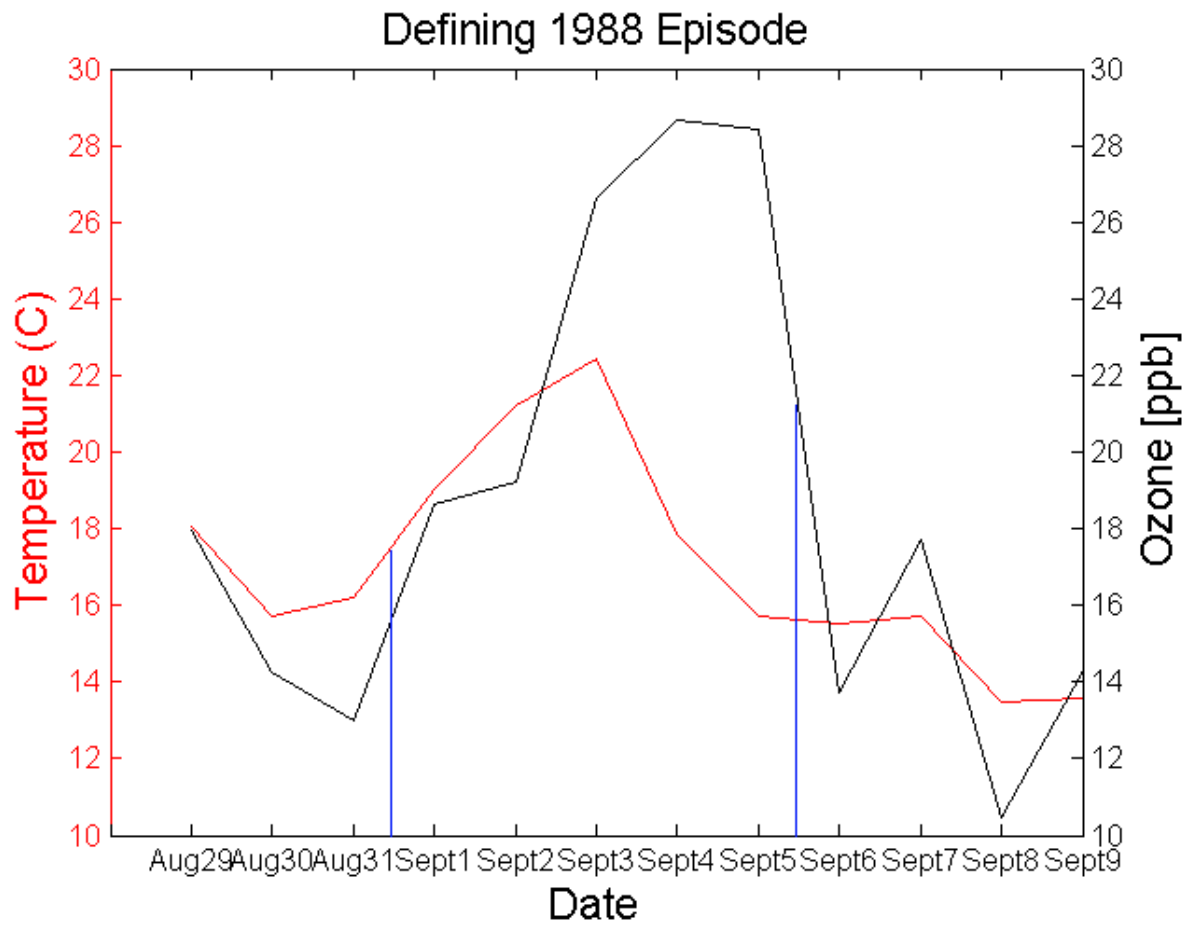


Figure A-1. Plot of mean daily temperature (red) and ozone concentration (black) for combined YVR and YXX locations, year 1988. Blue lines highlight the beginning and end of the episode.

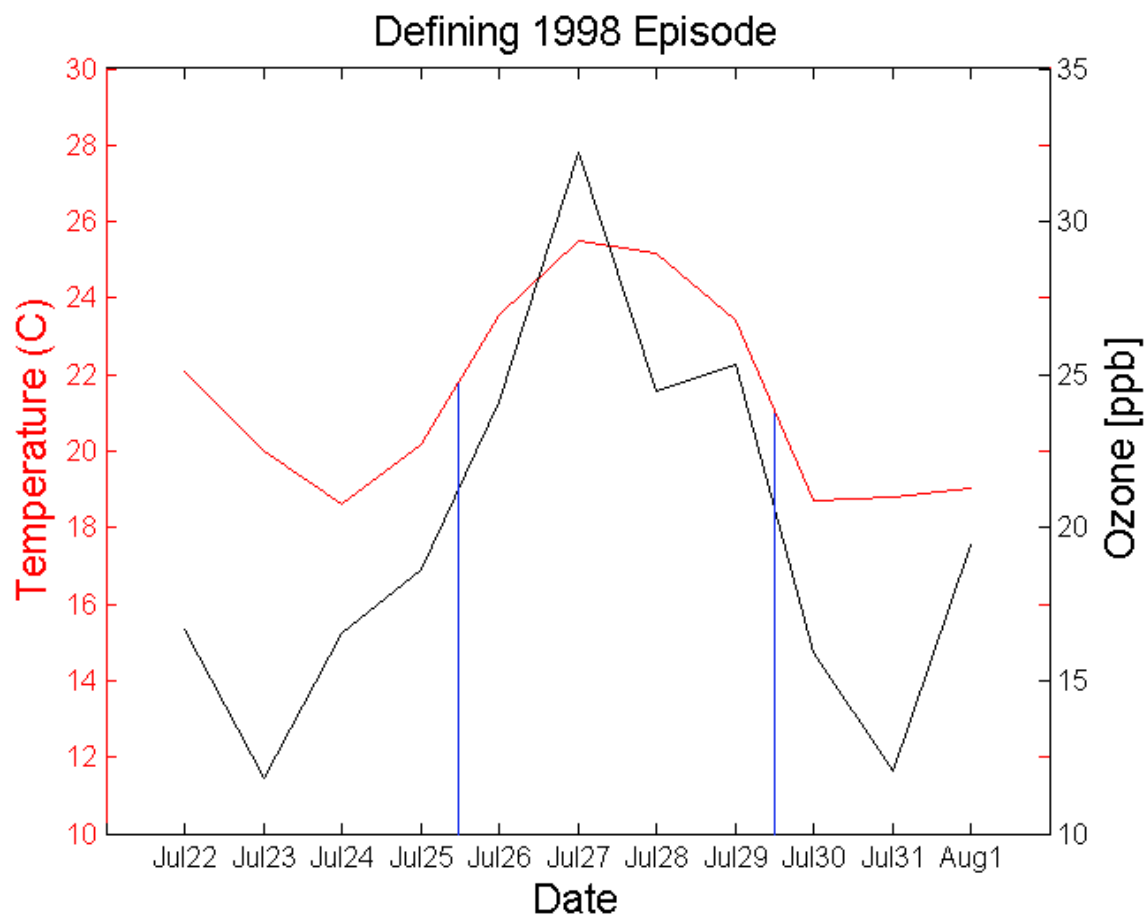


Figure A-2. Plot of mean daily temperature (red) and ozone concentration (black) for combined YVR and YXX locations, year 1998. Blue lines highlight the beginning and end of the episode.

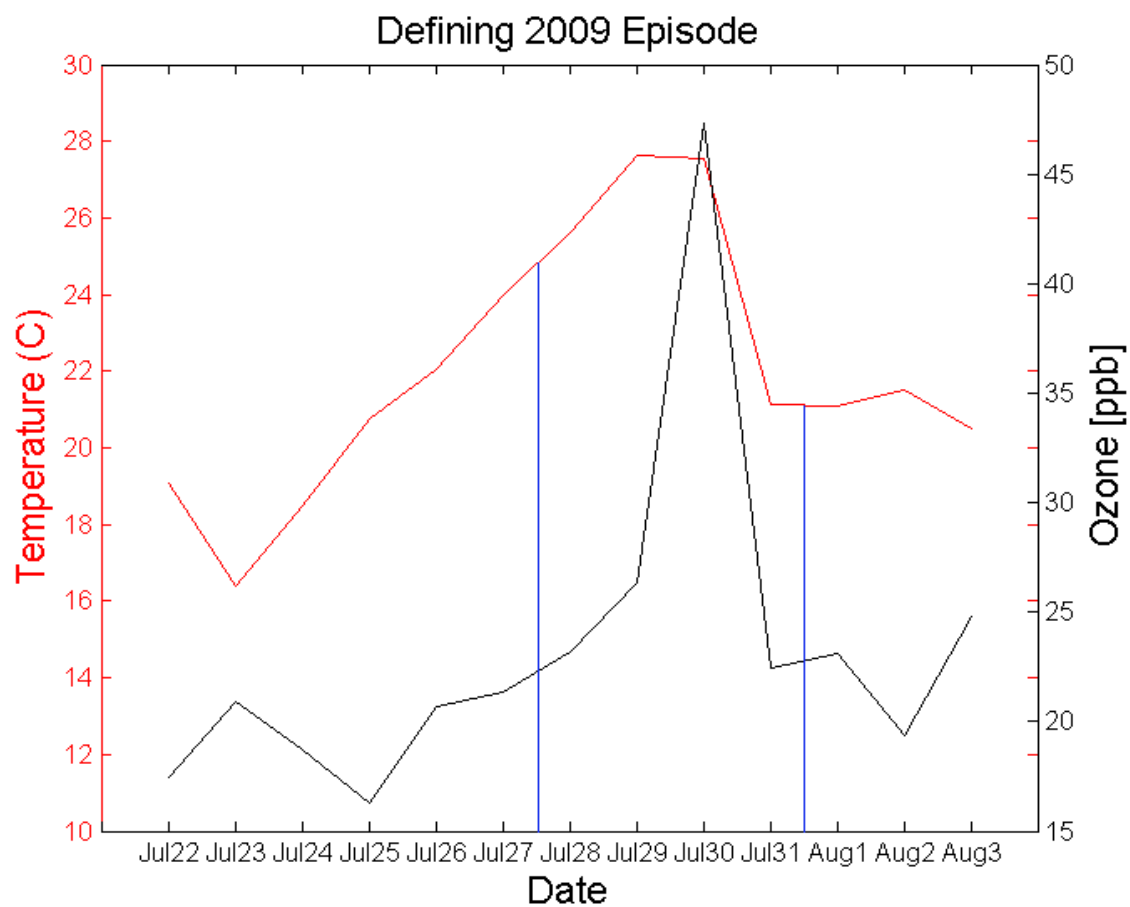


Figure A-3. Plot of mean daily temperature (red) and ozone concentration (black) for combined YVR and YXX locations, year 2009. Blue lines highlight the beginning and end of the episode.

APPENDIX B. Analysis of Ambient Ozone Data

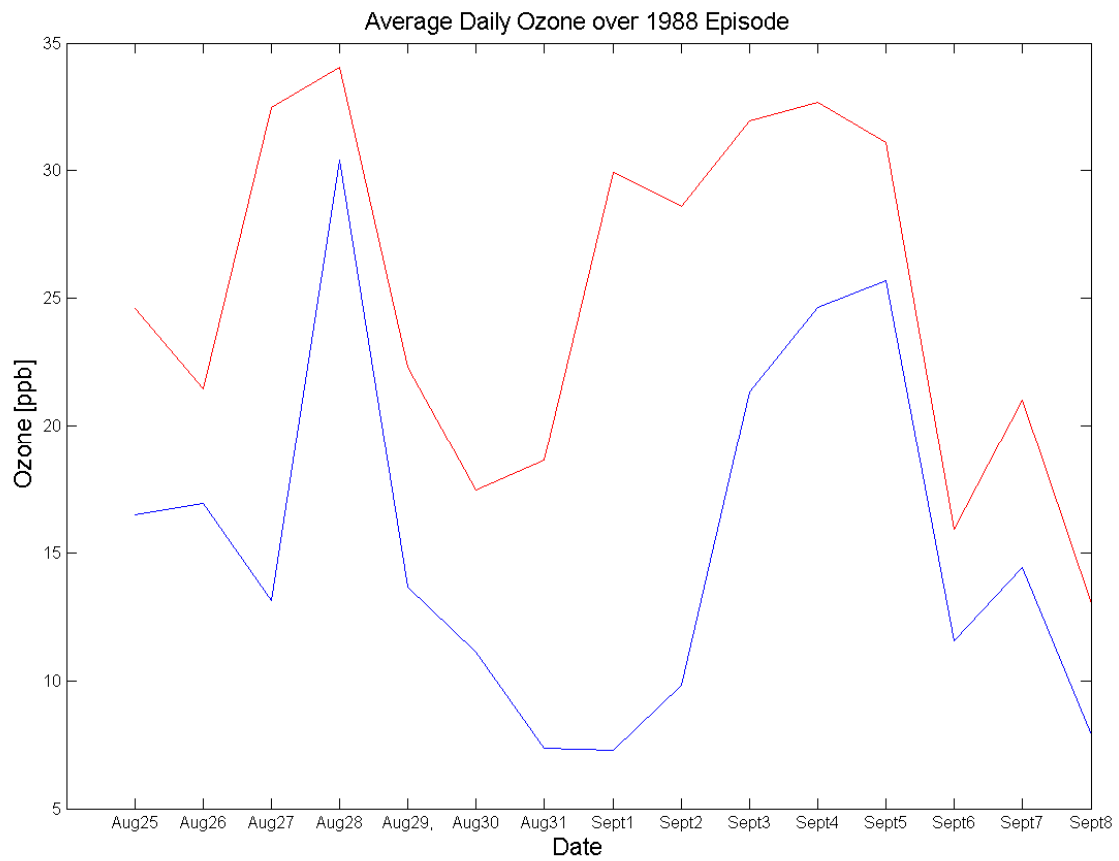


Figure B-1 Average daily (mean over 24 hours) ground level ozone at YVR (blue) and YXX (red), 1988.

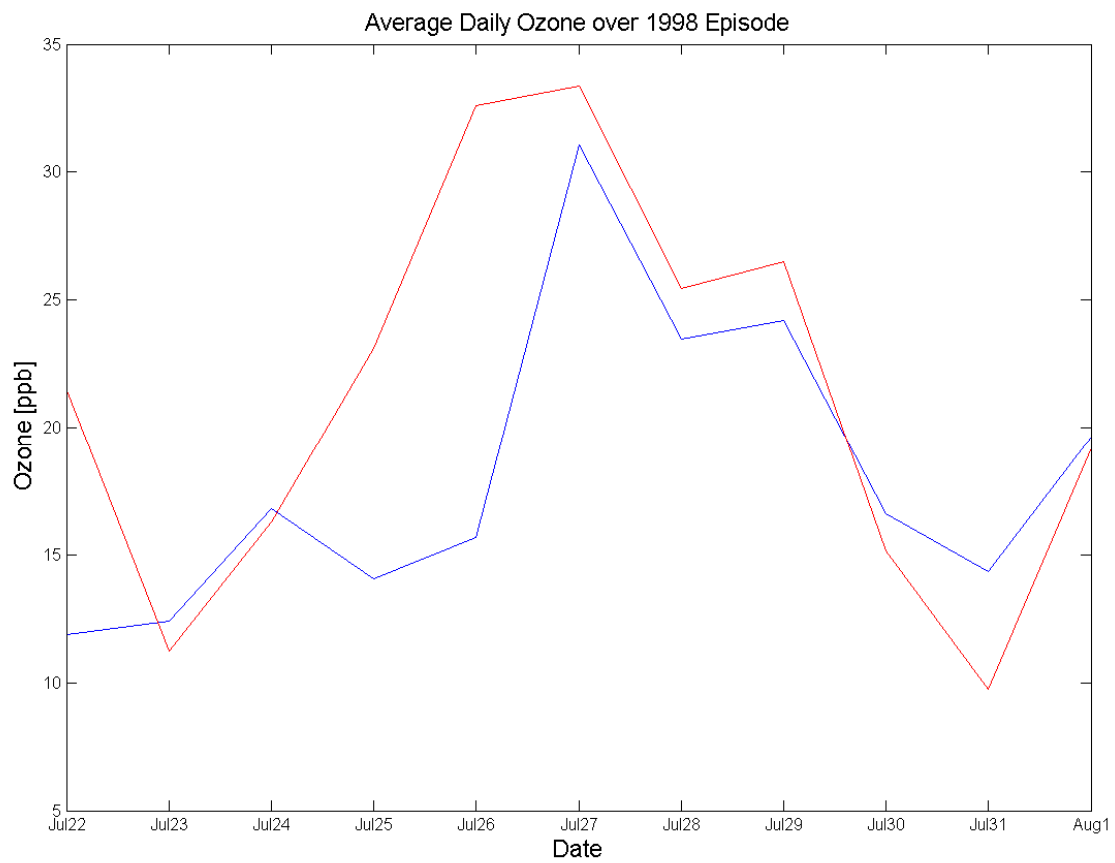


Figure B-1. Average daily (mean over 24 hours) ground level ozone at YVR (blue) and YXX (red), 1998.



Figure B-2. Average daily (mean over 24 hours) ground level ozone at YVR (blue) and YXX (red), 2009.

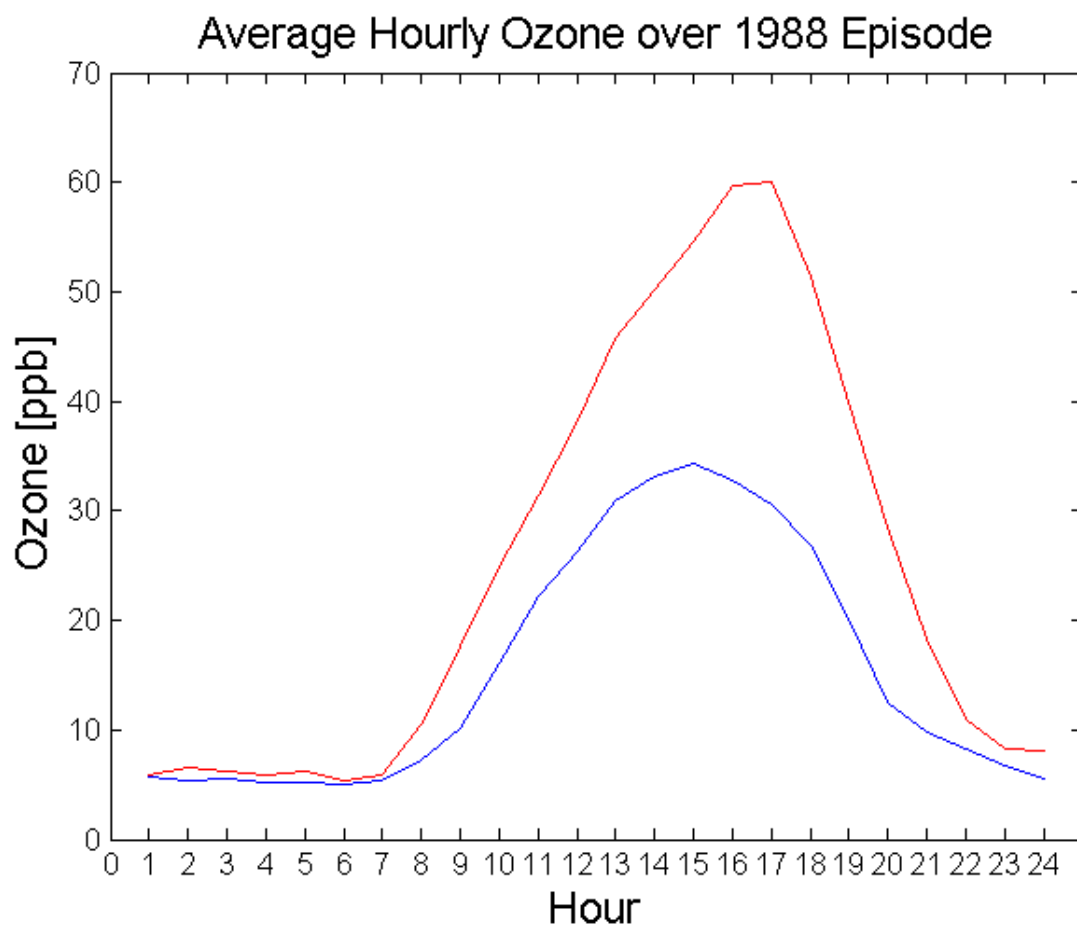


Figure B-3. Mean hourly ozone concentration at YVR (blue) and YXX (red), averaged over 1988 episode days September 1 – September 5.

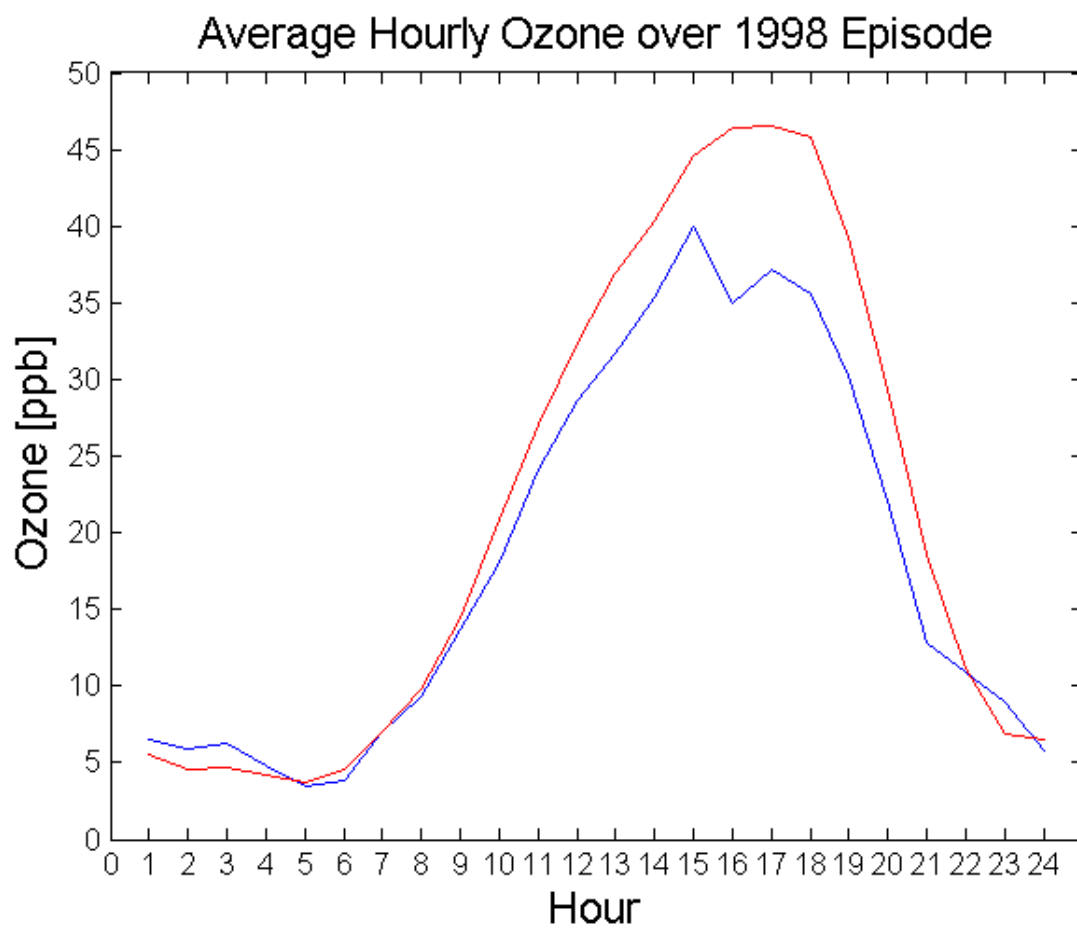


Figure B-4. Mean hourly ozone concentration at YVR (blue) and YXX (red), averaged over 1998 episode days July 26 – July 29.

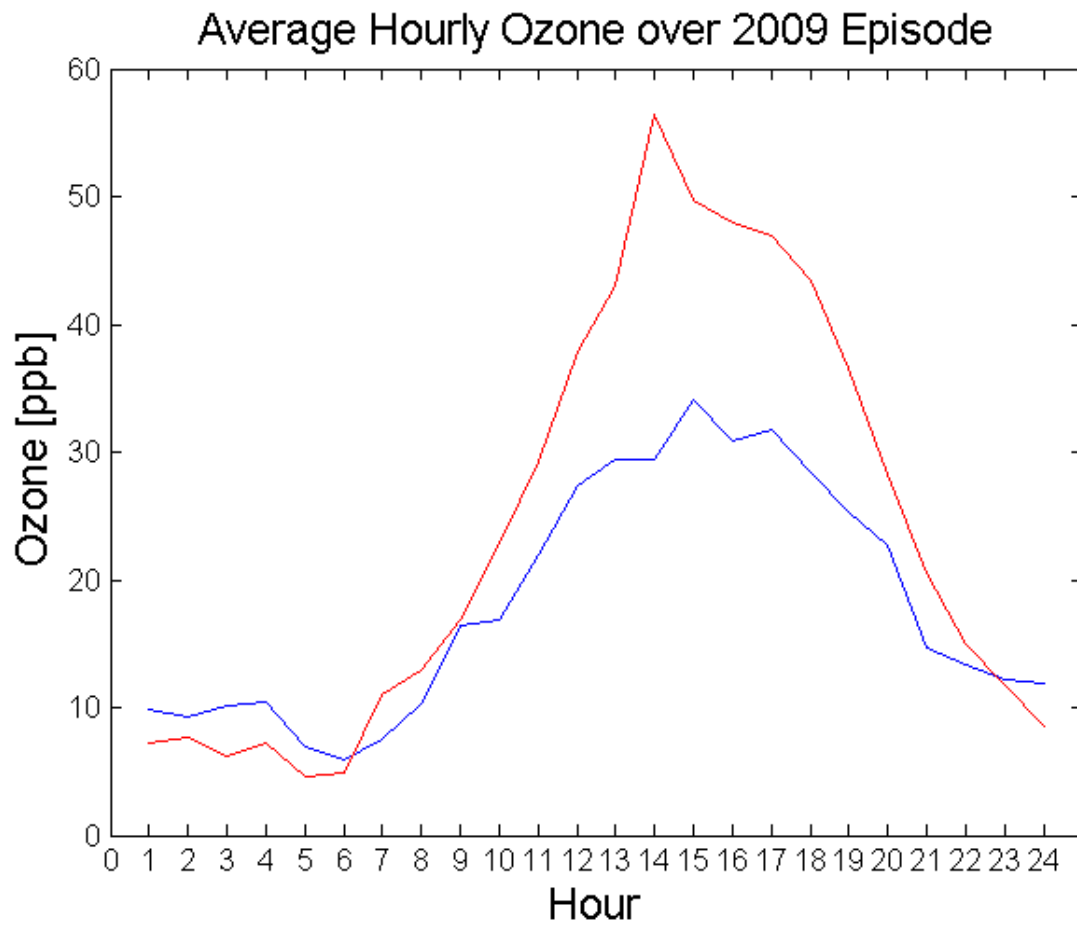


Figure B-5. Mean hourly ozone concentration at YVR (blue) and YXX (red), averaged over 2009 episode days July 28 – July 21.



Figure B-7. Spatial distribution of ozone plume over LVF on September 2, 1988. Source: Steyn *et al* (1999).

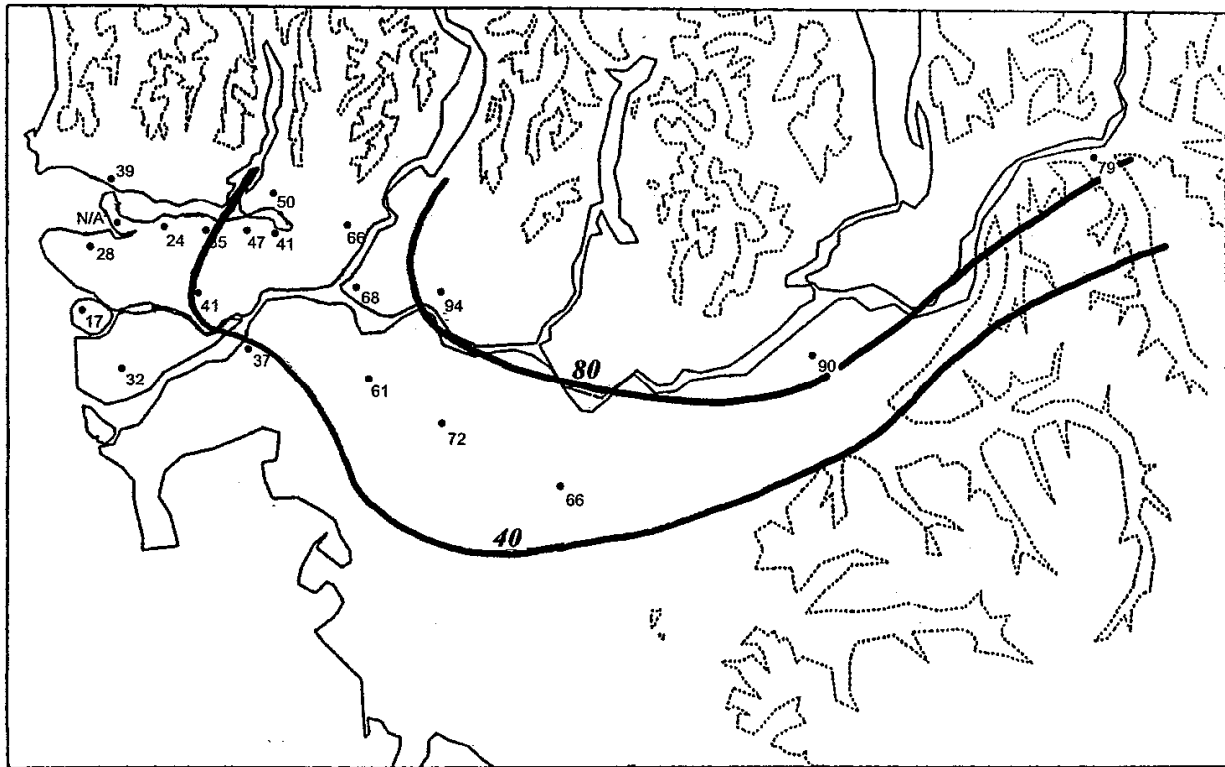


Figure B-8. Spatial distribution of ozone plume over LVF on July 26, 1998. Source: Steyn *et al* (1999).

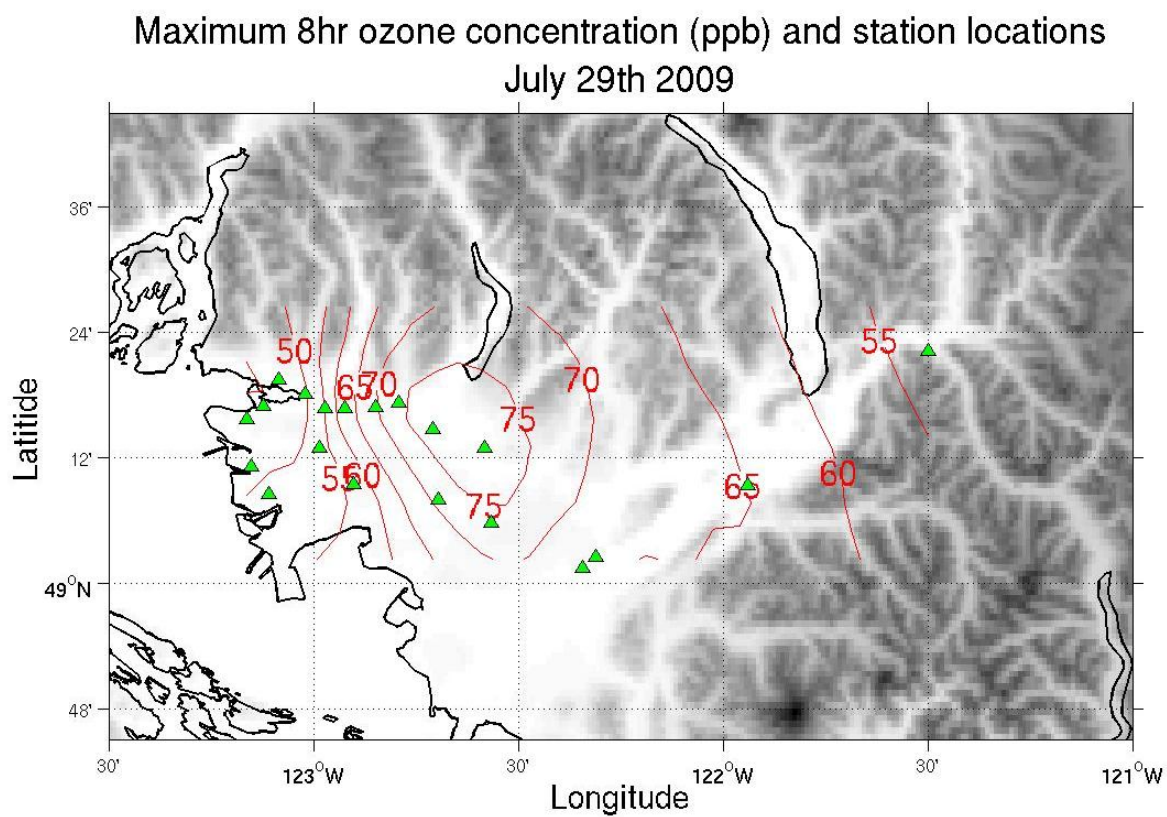


Figure B-9. Spatial distribution of ozone plume over LVF on July 29, 2009.

APPENDIX C. Analysis of Meteorological Data

C-1. Temperature

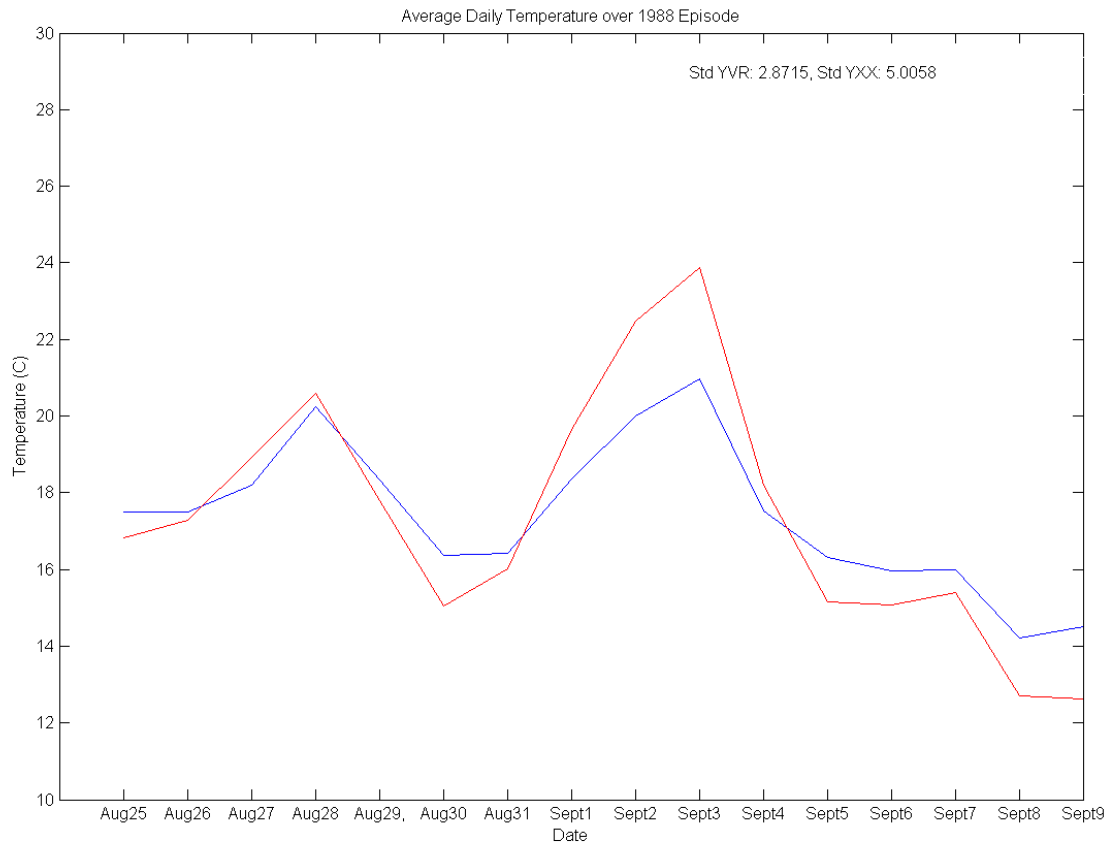


Figure C-1.1 Daily mean temperature plot for YVR (blue) and YXX (red) for August 25 – September 9, 1988.

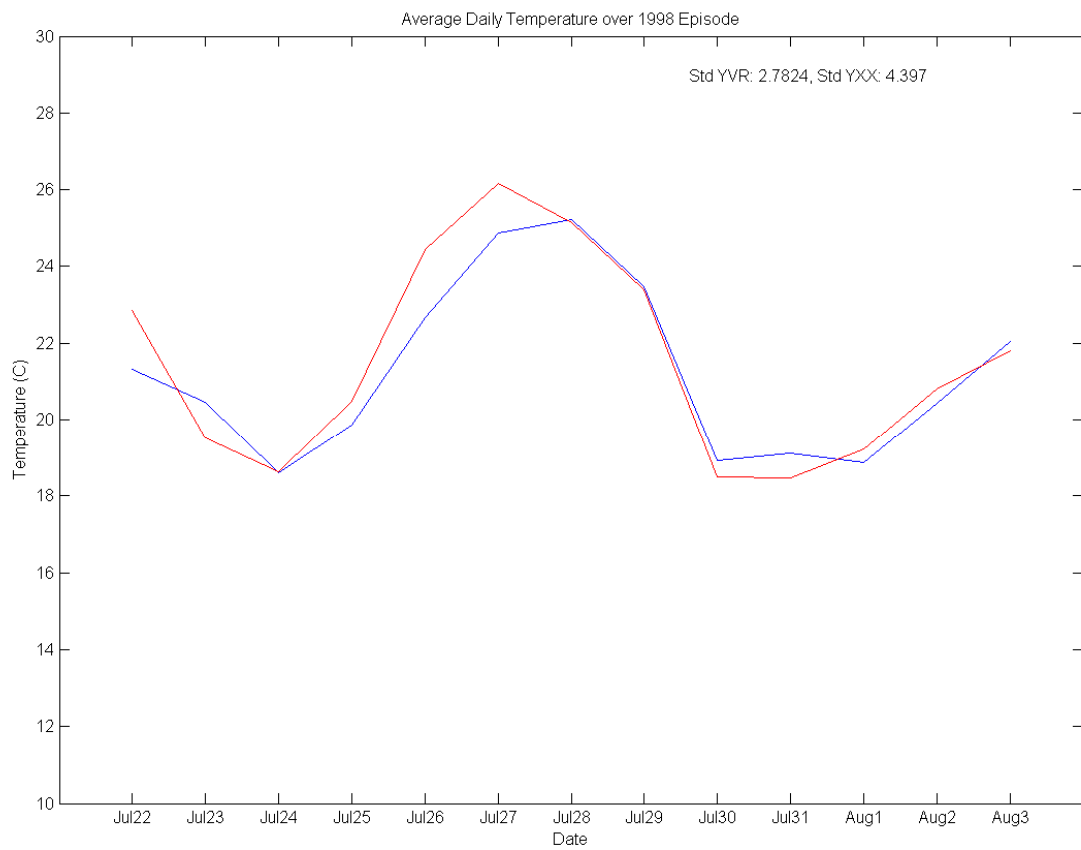


Figure C-1.2 Daily mean temperature plot for YVR (blue) and YXX (red) for July 22 – August 3 1998.

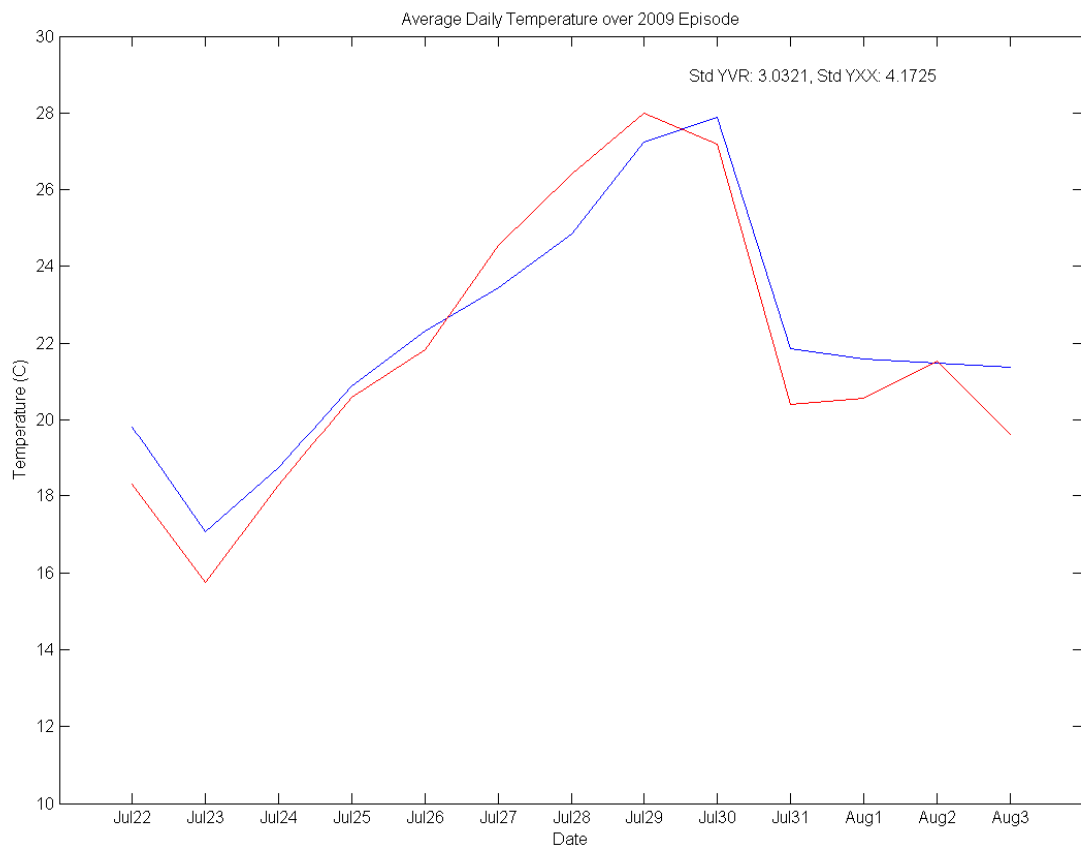


Figure C-1.3. Daily mean temperature plot for YVR (blue) and YXX (red) for July 22 – August 3 2009.

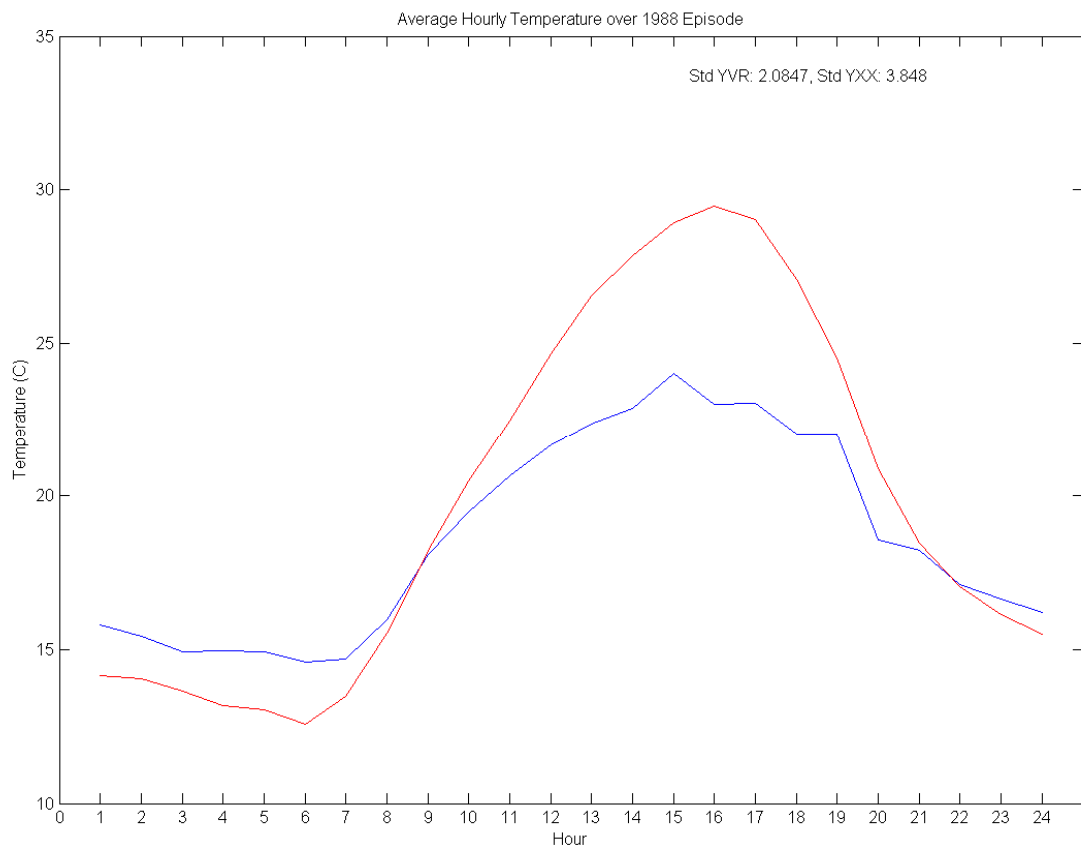


Figure C-1.4 Hourly mean temperature for YVR (blue) and YXX (red) over 1988 episode. Dates included in the average: September 1 – September 2, 1988.

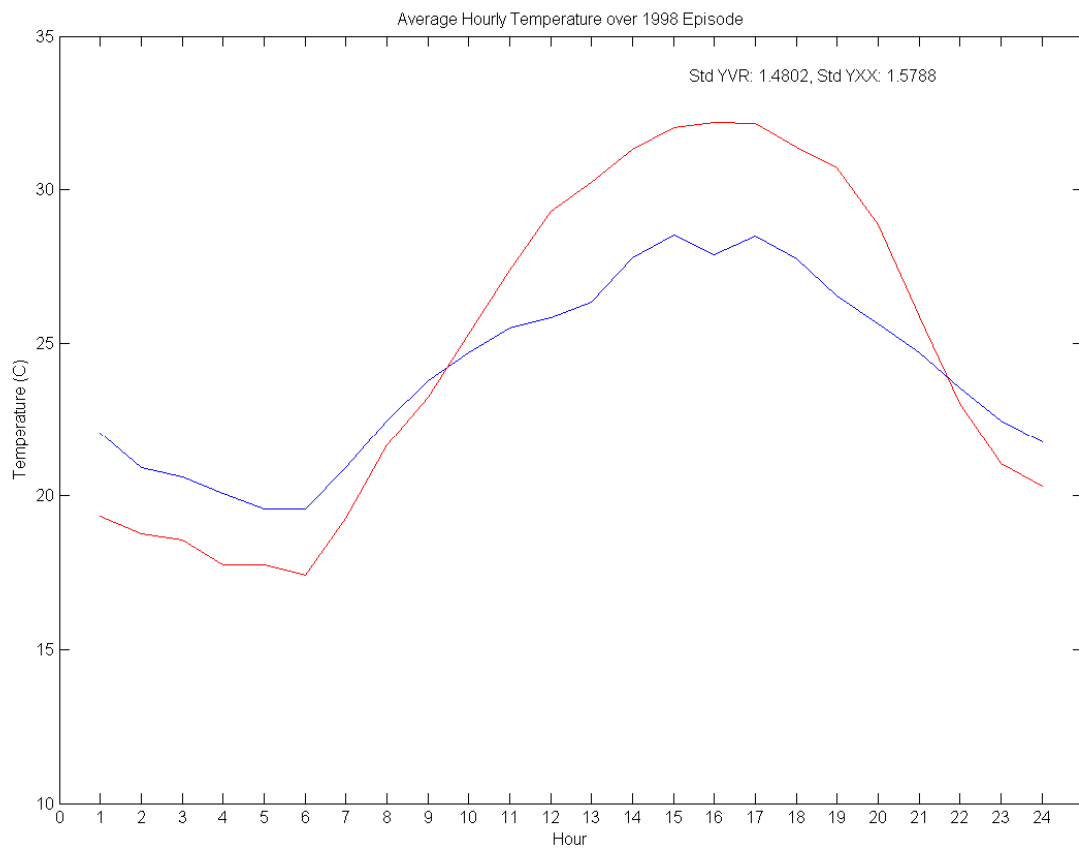


Figure C-1.5 Hourly mean temperature for YVR (blue) and YXX (red) over 1998 episode. Dates included in the average: July 26 – July 29, 1998.

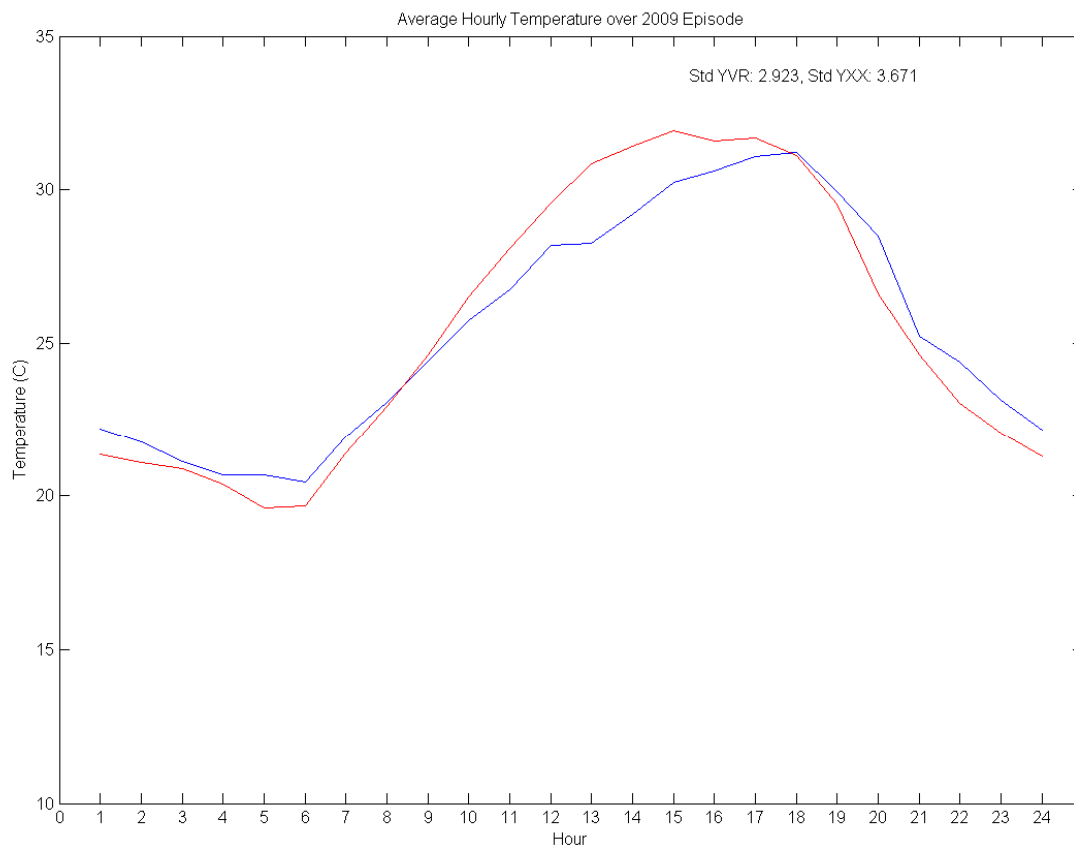


Figure C-1.6. Hourly mean temperature for YVR (blue) and YXX (red) over 2009 episode. Dates included in the average: July 28 – July 31, 2009.

C-2. Wind

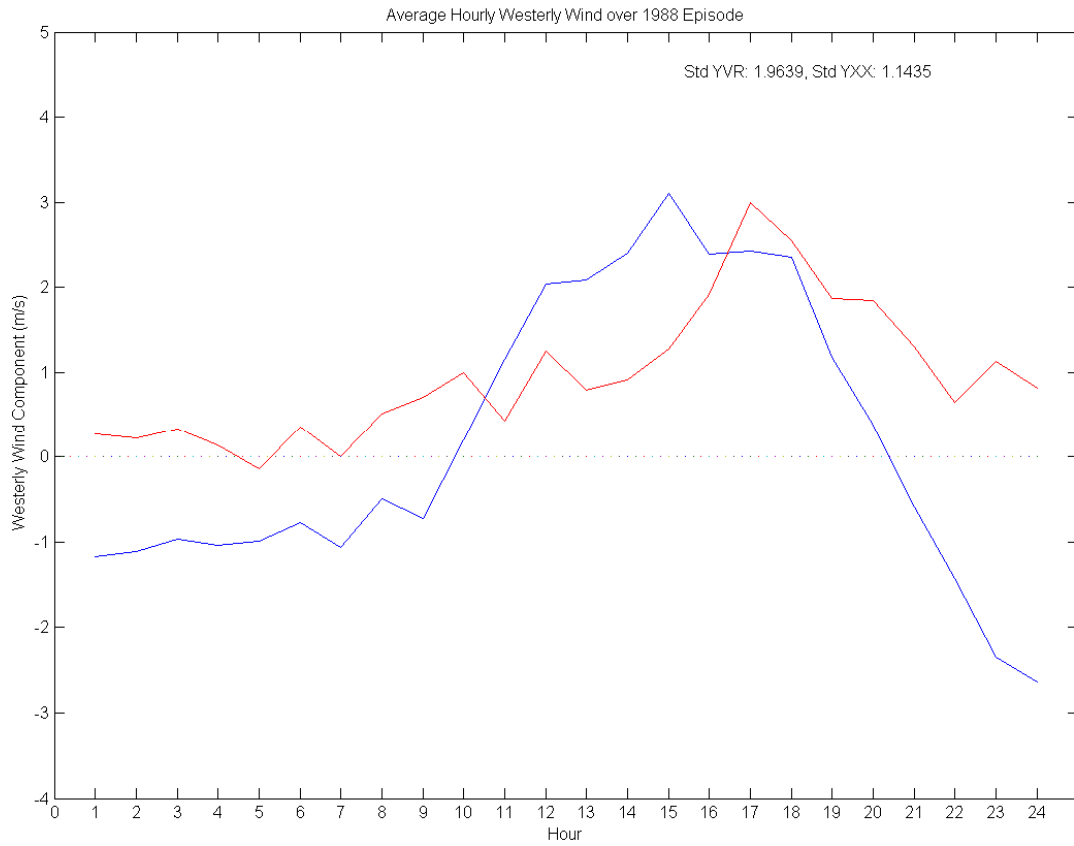


Figure C-2.1 Plot of mean westward wind component at YVR (blue) and YXX (red) averaged over 5 episode days: September 1 – September 5, 1988.



Figure C-2.2 Plot of mean westward wind component at YVR (blue) and YXX (red) averaged over 4 episode days: July 26 – July 29, 1998.

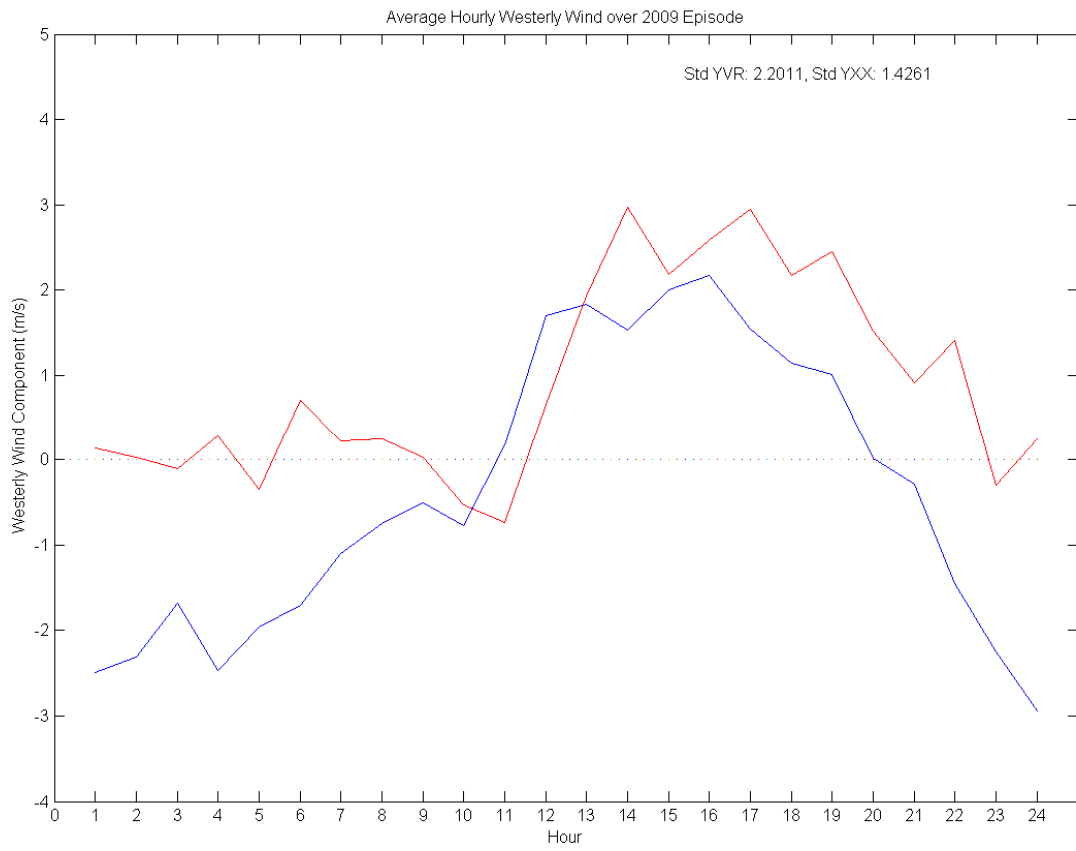


Figure C-2.3. Plot of mean westward wind component at YVR (blue) and YXX (red) averaged over 4 episode days: July 28 – July 31, 2009.

C-3. YVR Hodographs

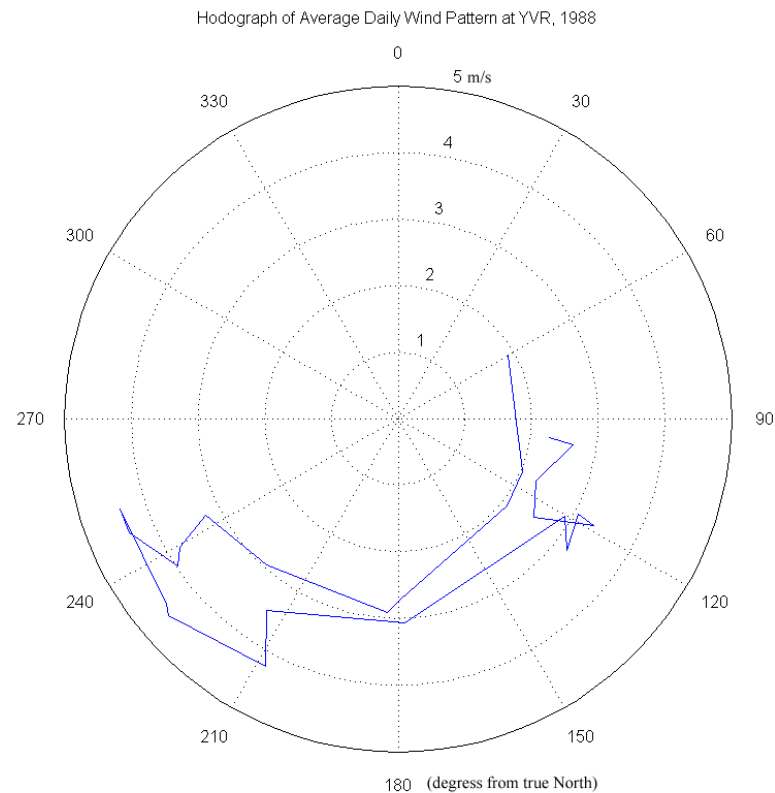


Figure C-3.1 Hodograph of average daily wind pattern at YVR for 1988 episode.

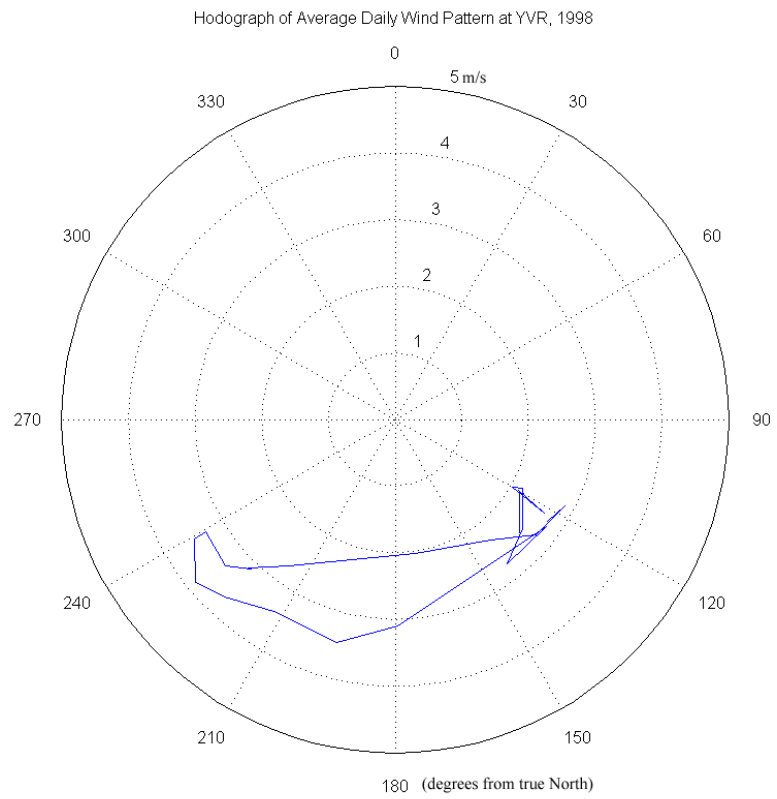


Figure C-3.2 Hodograph of average daily wind pattern at YVR for 1998 episode.

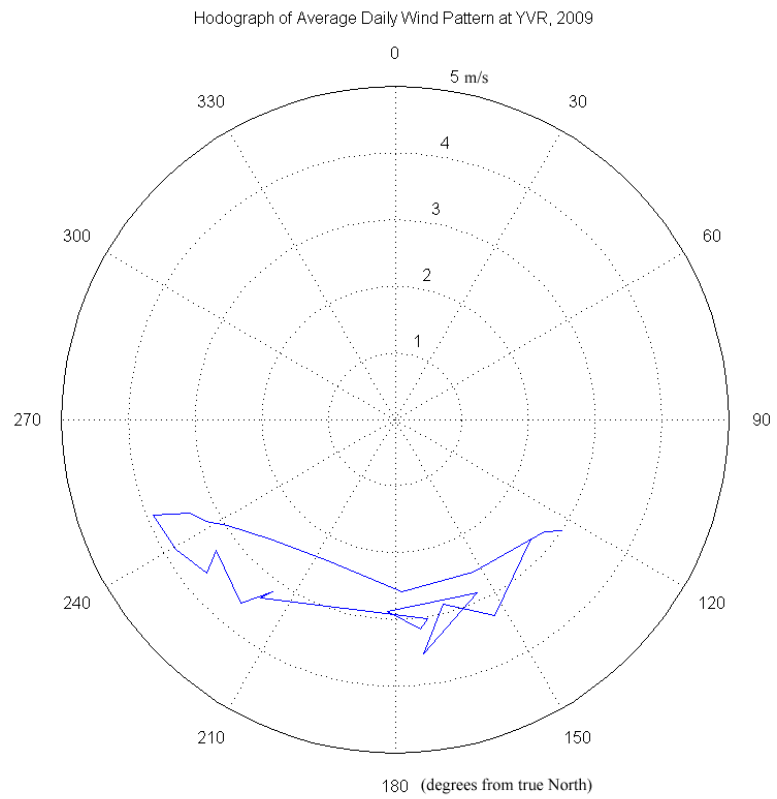


Figure C-3.3 Hodograph of average daily wind pattern at YVR for 2009 episode.

APPENDIX D. Mixed Layer Depth Simulation Code

The model was translated into MATLAB from original code in FORTRAN IV developed by Douw Steyn (1980). Sample simulation of mixed layer depth for August 1, 1988.

%% Script for interpolating Qh and modeling MLD

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Input for constant calculations:
P1=0.7;
P2=1.00;
ITS=65;
FB=0.45;
G_0=0.0124;

Qh=[-26.7 24.3 67.4 104.6 170.9 170.4 210.3 213.7 147.7 239.2 ...
    369.3 261.8 161.0 13.7 10.8]; %Input sensible heat flux

gam=[0.0200 0.0320 0.0440 0.0368 0.0248 0.0128 0.0134 0.0144 0.0154 ...
    0.0165 0.0175 0.0185 0.0195 0.0196]; %input Gamma
U_bar=[1.4 2.4 2.6 2.8 2.4 2.6 2.6 2.7 3.3 4.9 4.3 4.2 4.6 3.9]; %Input wind
Theta=[134.0 145.0 162.0 158.0 166.0 182.0 179.0 204.0 224.0 ...
    152.0 150.0 149.0 146.0 138.0]; %input Theta
Zi_0=35.0; %initial inversion height
Theta_0=290.0; %mixed layer temperature (K)
Beta=5.2000e-6; %synoptic horizontal divergence (s^-1)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%Number of hours to be analyzed
hour=1:15;
hour_i=1:0.1:15; %6 minute intervals
Qhi=interp1(hour,Qh,hour_i,'linear'); %interpolation

C=0.2; %entrainment parameter
REL=1.0e-10; %error
ABS=1.0e-10; %error
dT_0=0.1;

for iHour=1:14
    if iHour==1
        j=1;
    else
        j=(iHour-1)*10+1;
    end

    for iPeriod=j:10*iHour
        %compute fetch of urban surface for elliptical city
        RS=7.00;
        THES=0.3937;
        if Theta(iHour)<90.0
```

```

        PHI=(270.0+Theta(iHour))*1.7453e-3;
    else
        PHI=(Theta(iHour)-90.0)*1.7453e-2;
    end
    CS=cos(PHI)*2;
    SI=sin(PHI)*2;
    RP=sqrt(7053.0/196.0*SI+36.0*CS);
    DX=1000.0*( (RP*cos(PHI)+RS*cos(THES))*2+ ...
        (RP*sin(PHI)+RS*sin(THES))*2)*0.5;
    if Qhi(iPeriod)>0
        %set coefficients A1 to A7
        A(1)=Qhi(iPeriod)*(1+C)/1212;
        A(2)=0.7171*sqrt(U_bar(iHour)*Qhi(iPeriod)*P1*gam(iHour)/(1212.0*DX));
        A(3)=C*Qhi(iPeriod)/1212.0;
        if iPeriod>=ITS
            A(4)=Beta*exp(FB*0.1*(iPeriod-ITS));
        else
            A(4)=Beta;
        end
    end
    A(5)=sqrt(U_bar(iHour)*Qhi(iPeriod)*(1.0+2.0*C)/(2424.0*gam(iHour)*P1*DX));
    A(6)=gam(iHour)*P1;
    A(7)=Beta*G_0;
    TIS=360.0*iPeriod;
    Ti=0.0;
    Tf=360.0;
    %set array values of inversion height, mean temperature and
    if Qhi(iPeriod-1)<0
        V(1)=Theta_0;
        V(2)=Zi_0;
        V(3)=dT_0;
    else
        V(1)=Sol(size(T,1),1);
        V(2)=Sol(size(T,1),2);
        V(3)=Sol(size(T,1),3);
    end

    options = odeset('RelTol',REL,'AbsTol',ABS);
    [T,Sol] = ode45(@(T,V) diffEqSys(T,V,A,Beta,TIS),[Ti Tf],V,options);
    ZiResult(iPeriod)=Sol(size(T,1),2);
    ThetaResult(iPeriod)=Sol(size(T,1),1);
    dTResult(iPeriod)=Sol(size(T,1),3);

end
end
end

```

APPENDIX E. Supplementary Material

E-1. Ozone Time Series

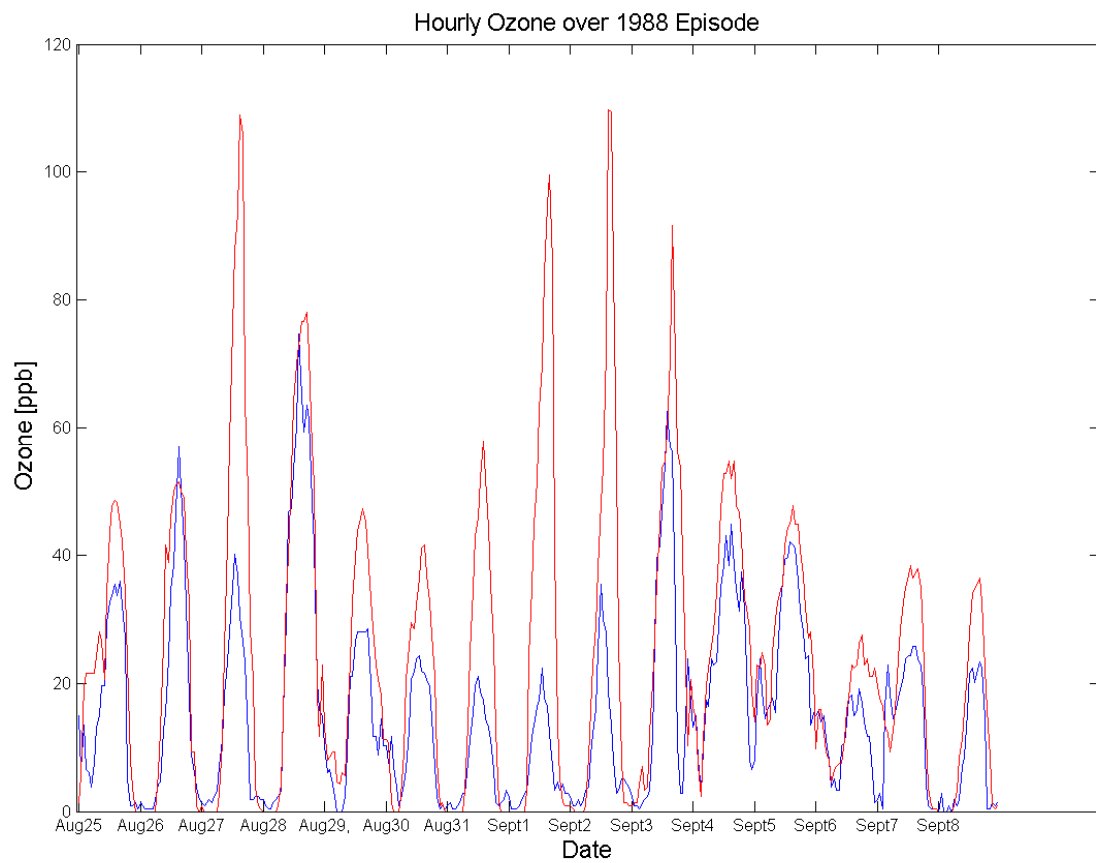


Figure E-1.1 Ground level ozone time series plot for 1988 episode based on hourly averages for YVR (blue) and YXX (red)..

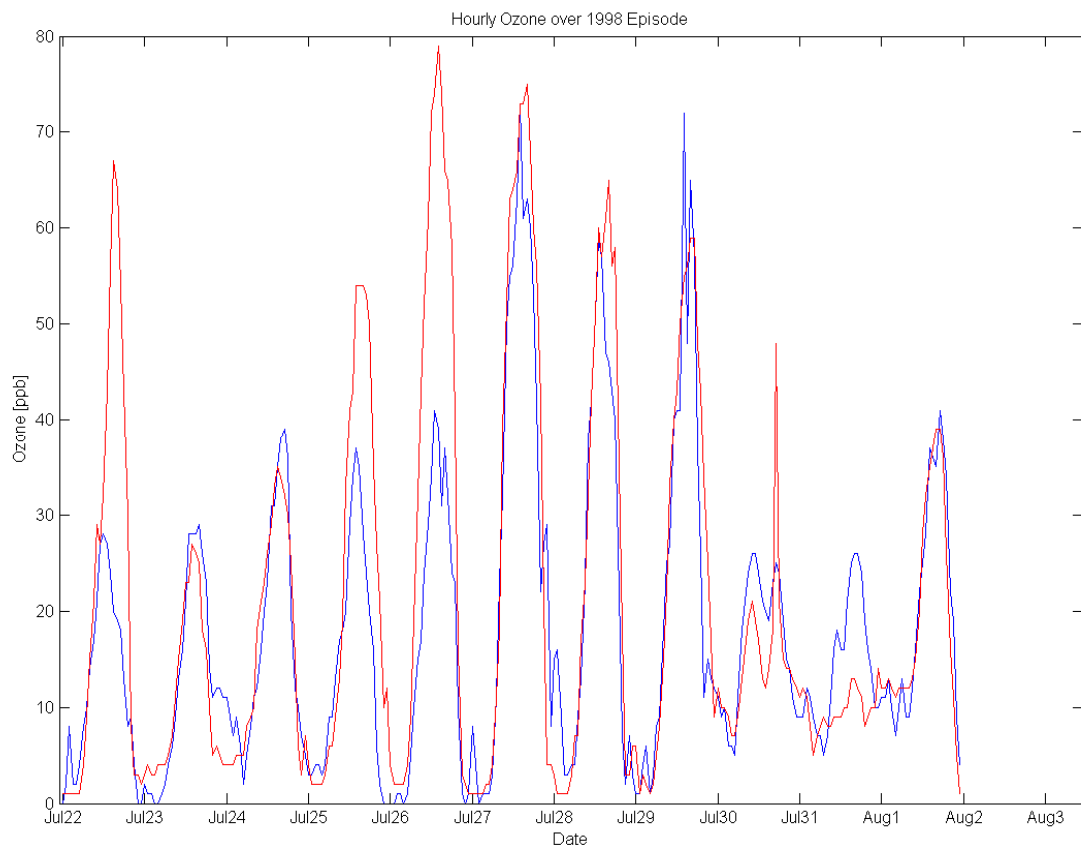


Figure E-1.2. Ground level ozone time series plot for 1998 episode based on hourly averages for YVR (blue) and YXX (red)..

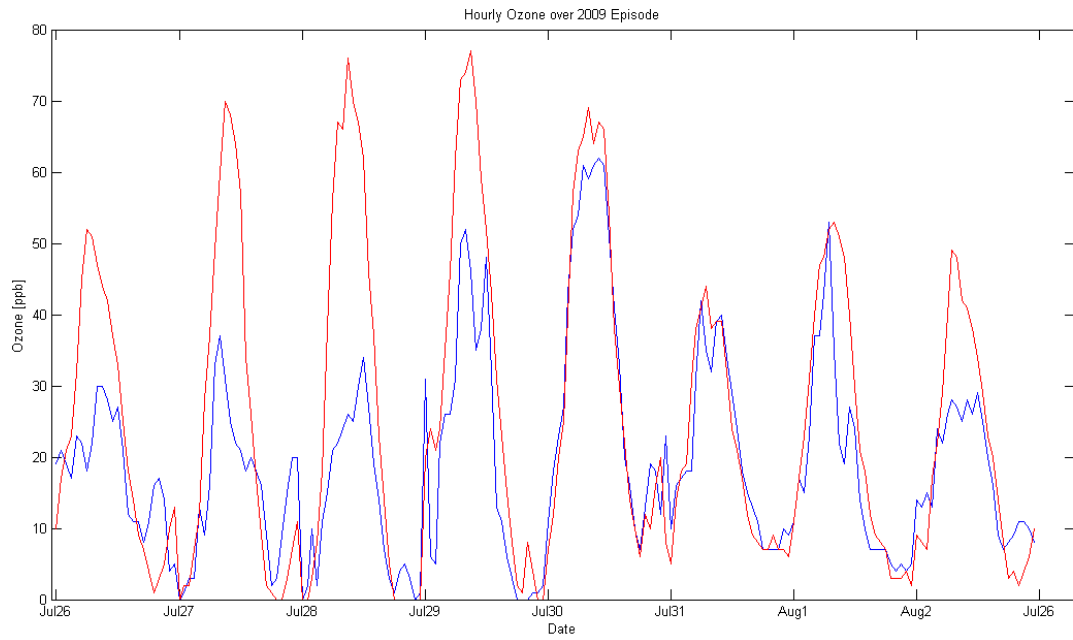


Figure E-1.3 Ground level ozone time series plot for 2009 episode based on hourly averages for YVR (blue) and YXX (red).

E-2. Temperature Time Series

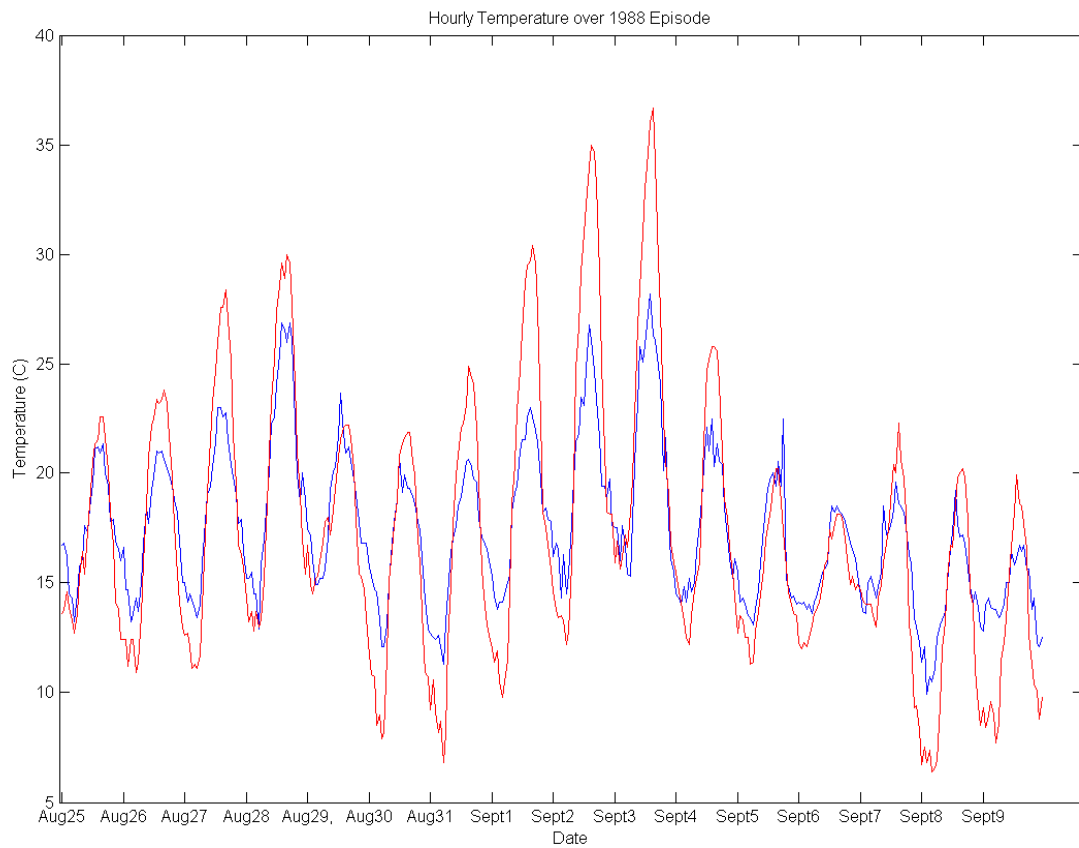


Figure E-2.1. Time series plot for mean hourly ground level temperature at YVR (blue) and YXX (red) for August 25-September 9, 1988.

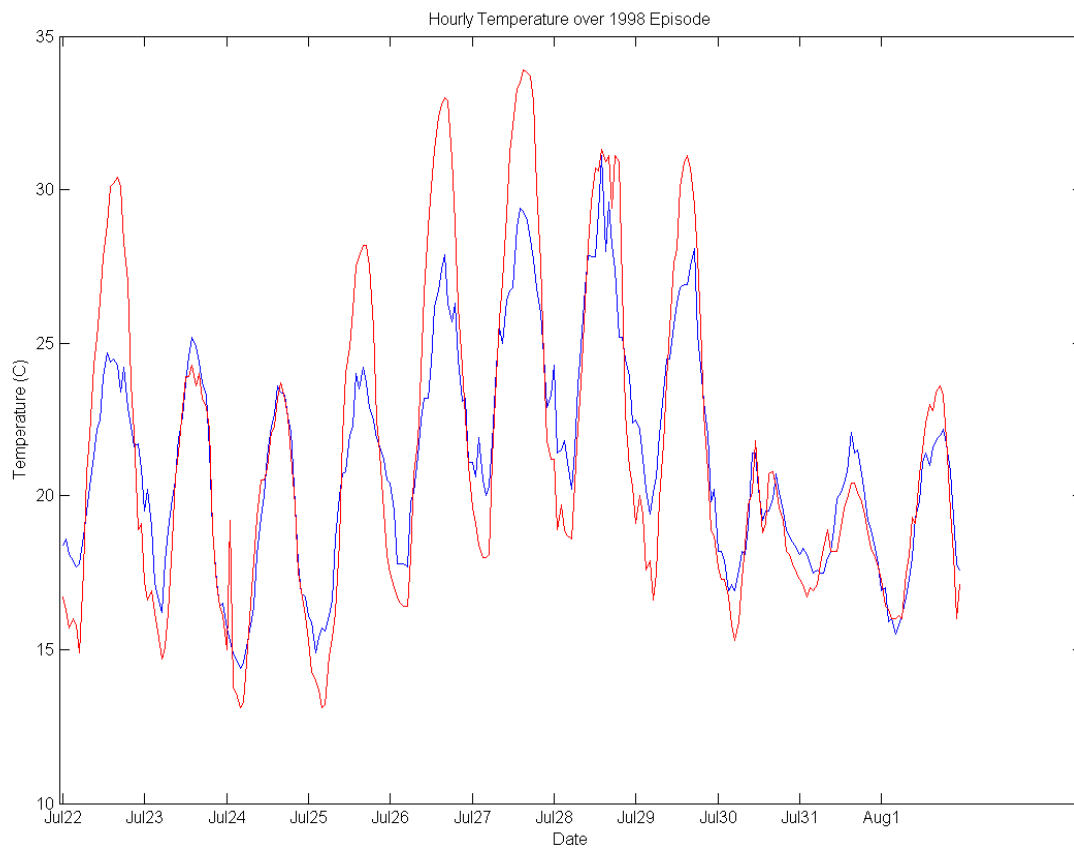


Figure E-2.2. Time series plot for mean hourly ground level temperature at YVR (blue) and YXX (red) for July 22-August 1, 1998.

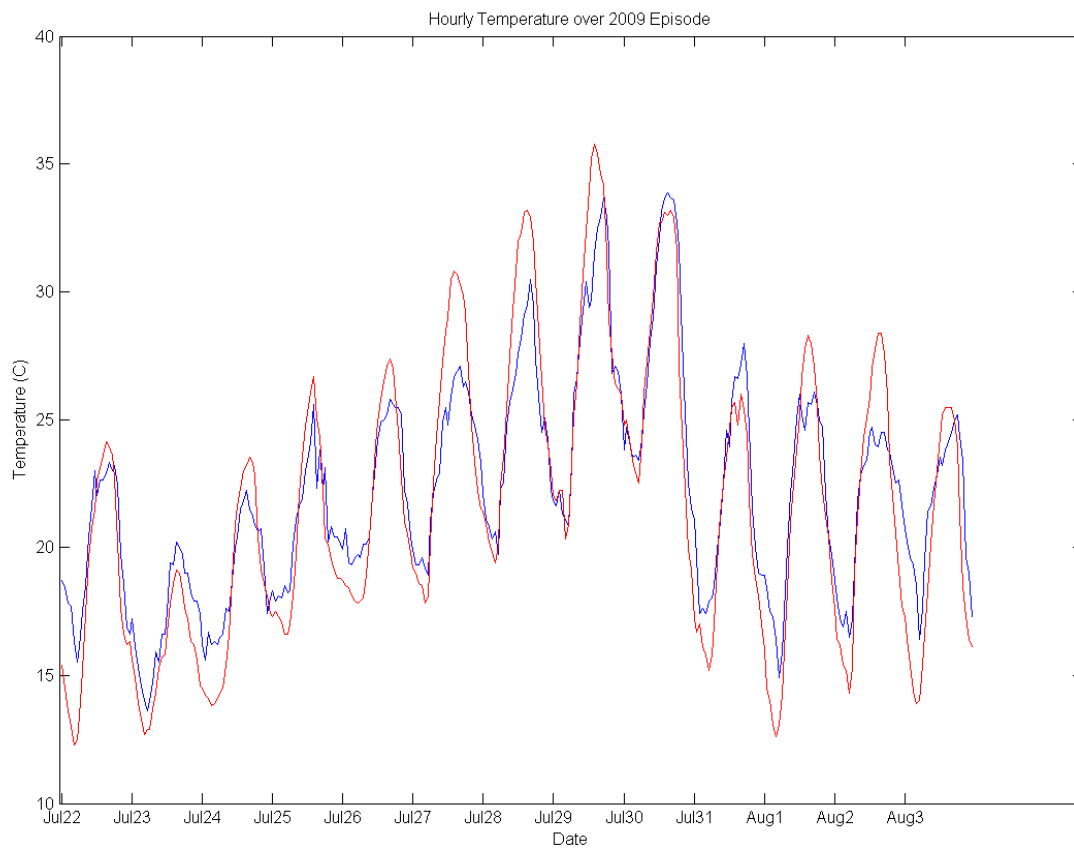


Figure E-2.3. Time series plot for mean hourly ground level temperature at YVR (blue) and YXX (red) for July 22 - August 3, 2009.

E-3. Wind-rose Plotting

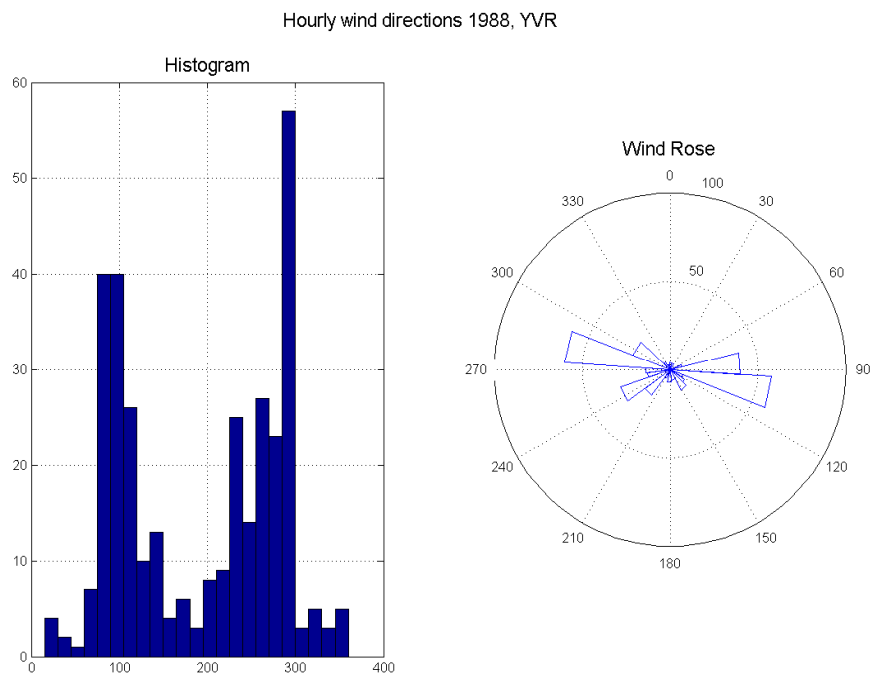


Figure E-3.1 Wind-rose plot and histogram for YVR wind direction, 1988. Both show the number of occurrences of a wind blowing in a given direction (degrees) throughout the episode.

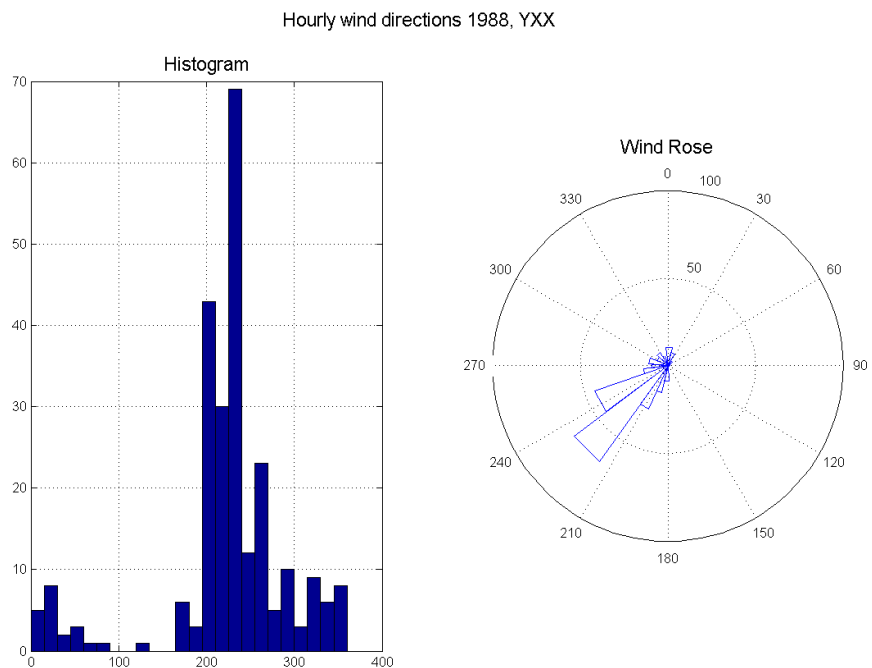


Figure E-3.2. Wind-rose plot and histogram for YXX wind direction, 1988. Both show the number of occurrences of a wind blowing in a given direction (degrees) throughout the episode.

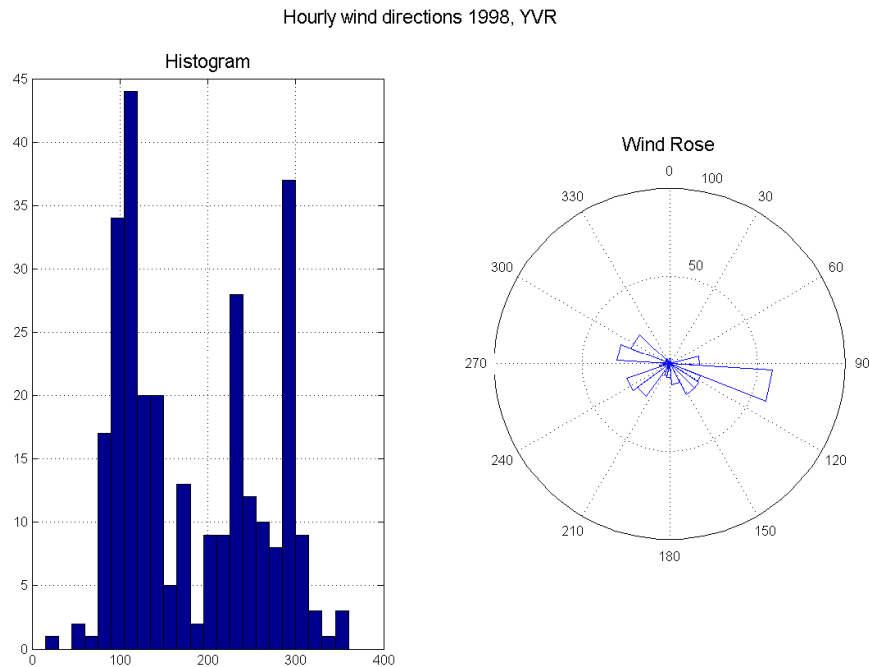


Figure E-3.3. Wind-rose plot and histogram for YVR wind direction, 1998. Both show the number of occurrences of a wind blowing in a given direction (degrees) throughout the episode.

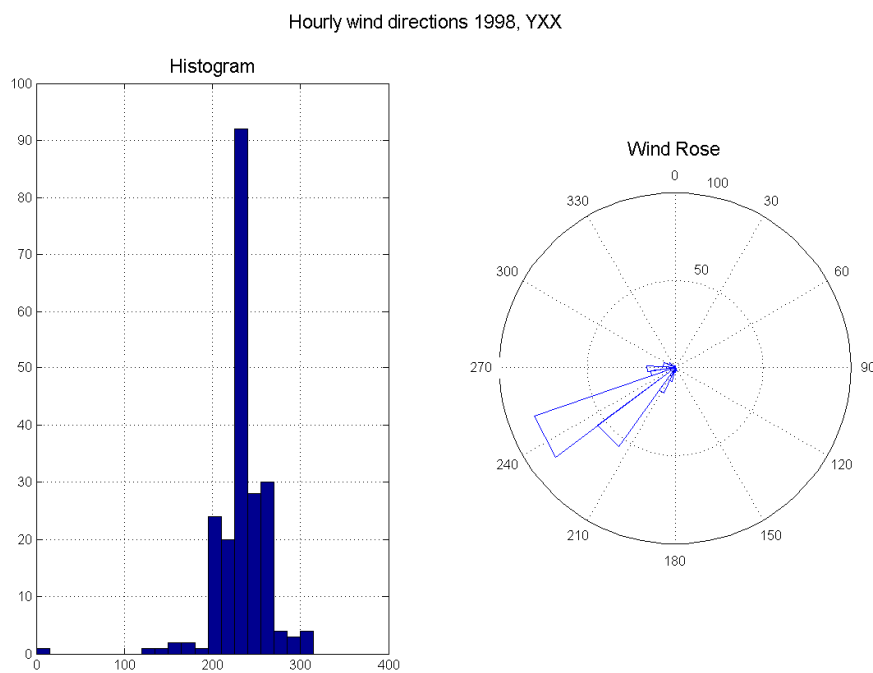


Figure E-3.4. Wind-rose plot and histogram for YXX wind direction, 1998. Both show the number of occurrences of a wind blowing in a given direction (degrees) throughout the episode.

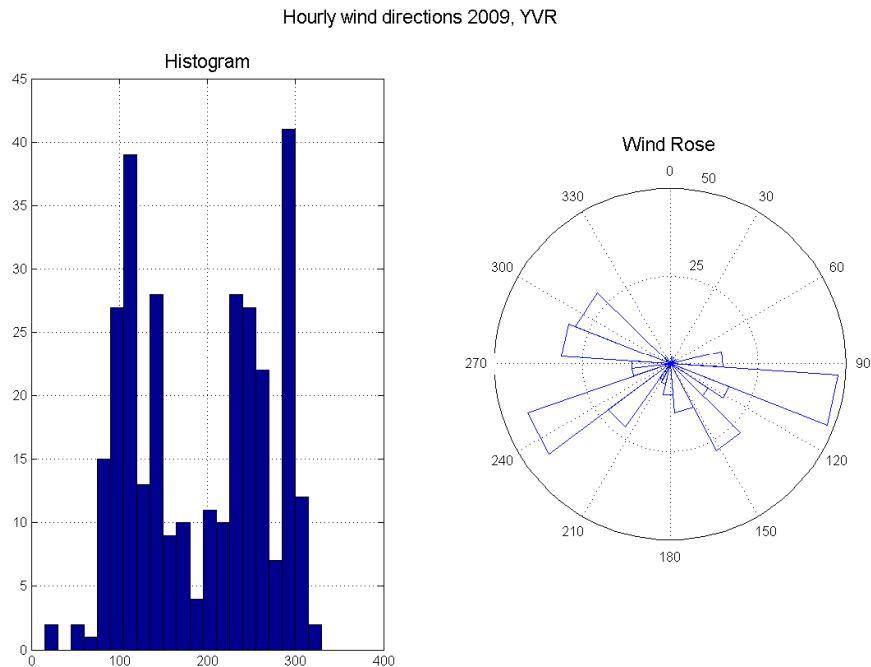


Figure E-3.5. Wind-rose plot and histogram for YVR wind direction, 2009. Both show the number of occurrences of a wind blowing in a given direction (degrees) throughout the episode.

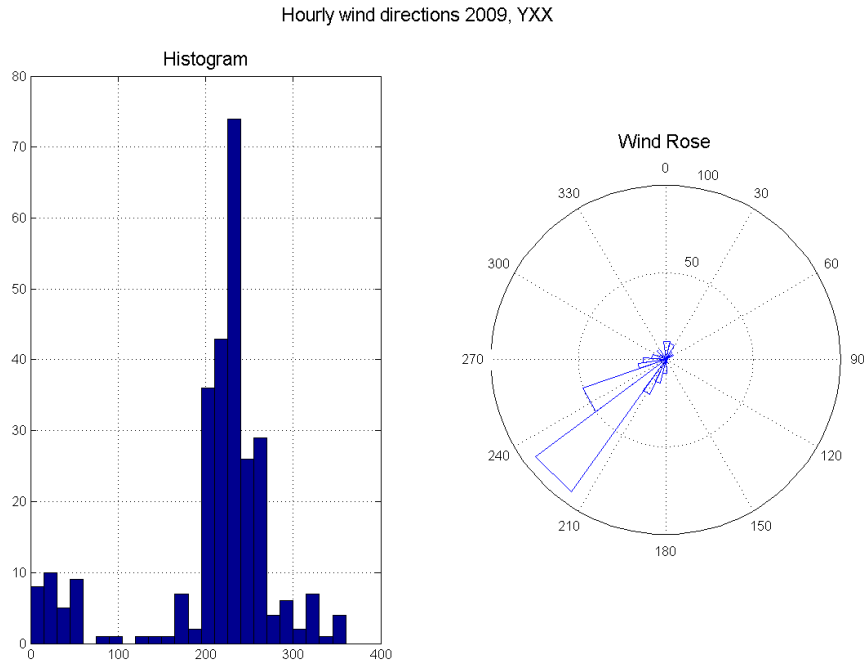


Figure E-3.6. Wind-rose plot and histogram for YXX wind direction, 2009. Both show the number of occurrences of a wind blowing in a given direction (degrees) throughout the episode.

E-4. Mixed Layer Depth Model Output

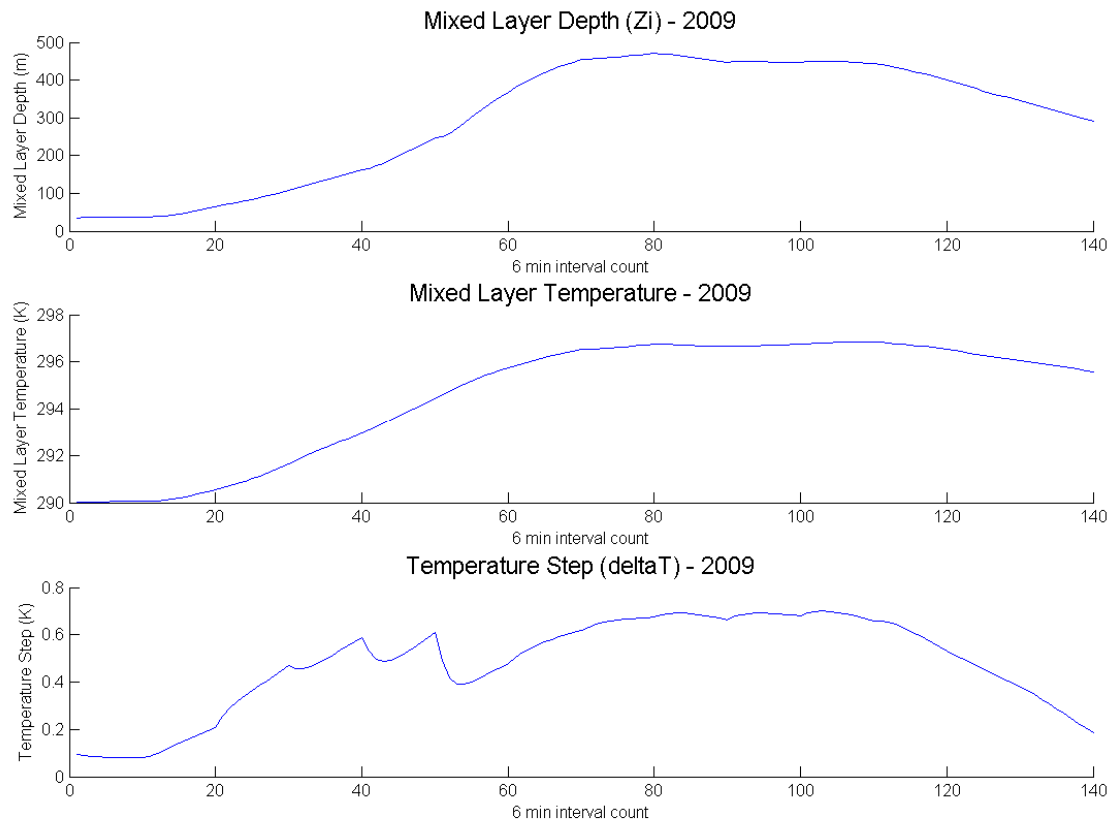


Figure E-4. Simulated mixed layer depth (Z_i), mixed layer temperature, and temperature step for 2009 episode.