Air Quality and Visibility in Southwestern British Columbia during Forest Fire Smoke Events

by

Jenna Christine Keane

B.Sc., Meteorology, Western Illinois University, 2010

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

Master of Science

in

THE FACULTY OF GRADUATE STUDIES

(Geography)

The University of British Columbia

(Vancouver)

August 2012

© Jenna Christine Keane, 2012
Abstract

In recent years, the frequency of forest fires has been increasing in western North America. With an increase in forest fire activity, attention has been drawn to the negative effects forest fire smoke has on air quality and visibility. This study quantifies the relationship between smoke, air quality and visibility. Determining how much smoke produced by forest fires influences air quality and visibility will improve air quality forecasting. This study was conducted from 2007 through 2011 during the fire season (April - October) in southwestern British Columbia, focusing on the Georgia Basin airshed.

A host of tools were used to determine how air quality and visibility were influenced by forest fire smoke. Satellite Fire Detection from National Oceanic and Atmospheric Administration (NOAA) ’s, National Geophysical Data Centre (NGDC) was used to determine on which days during the four year period smoke was present in southwestern British Columbia. To determine where smoke particles were transported from, NOAA’s HYbrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model was used. Backward trajectories were computed from Vancouver International Airport on days which smoke was present. PM$_{2.5}$ (particles with a diameter less than 2.5 microns) and O$_3$ (ozone) concentrations were examined at twelve locations. Gases and aerosols produced by forest fires are known to degrade visibility. A semi-automated approach was used to calculate visibility using digital images.

Southwestern British Columbia’s air quality and visibility was negatively influenced by smoke. Up to 30% of summer days in the Georgia Basin airshed were influenced by smoke. The summer of 2009 experienced the most smoke days. Smoke and aerosol concentrations were largely influenced by dominating weather
patterns. Two weather patterns dominate in the Georgia Basin airshed on smoke
days. One pattern creates favourable conditions to produce forest fires and the other
is likely to transport smoke from the interior of British Columbia into the Georgia
Basin airshed. Concentrations of PM$_{2.5}$ increased on average by 5 $\mu$gm $^{-3}$ and
O$_3$ increased by 7 ppb when smoke was present. Visual range (VR) decreased on
average by 60 km and estimated extinction values increased during smoke events.
Preface

Lidar imagery data used in Chapter 2 was provided by Paul Cottle, who is currently a Ph.D. student within the Earth and Ocean Science Department at UBC.

The weather typing catalog used in Chapter 3 was produced by Derek van der Kamp, who is a Ph.D. student at the UBC Department of Geography.

Chapter 4 was based on methods developed by Andrew Teakles and this co-workers at Environment Canada. During the summer of 2011, Andrew and I collaborated to develop and transfer his methods to compute image metrics.
Table of Contents

Abstract ......................................................... ii
Preface ............................................................ iv
Table of Contents .................................................... v
List of Tables ......................................................... viii
List of Figures ......................................................... ix
Glossary ............................................................. xi
Acknowledgments ..................................................... xii

1 Introduction ......................................................... 1
  1.1 Motivation for study ........................................... 1
  1.2 Project description ............................................ 2
  1.3 Background and methods ....................................... 3
    1.3.1 Frequency of forest fires in western North America .... 3
    1.3.2 Long-range transport of pollutants ....................... 4
    1.3.3 Biomass burning and smoke properties ................... 4
    1.3.4 Particulate matter and ozone ............................. 5
    1.3.5 Canada wide standards for particulate matter and ozone .. 6
    1.3.6 Health impacts related to particulate matter and ozone .. 6
    1.3.7 Atmospheric visibility .................................... 7
  1.4 Study area description ....................................... 8
1.5 Data analysis methods and data sets ........................................ 10
  1.5.1 Quality control ...................................................... 11
1.6 Project overview .......................................................... 11

2 Satellite Fire Detection and HYSPLIT ................................. 12
  2.1 Introduction .............................................................. 12
  2.2 Background ............................................................... 13
    2.2.1 HMS Satellite Fire Detection ...................................... 13
    2.2.2 HYSPLIT ............................................................. 14
    2.2.3 Synoptic weather patterns and yearly weather trends ......... 14
  2.3 Methods ................................................................. 15
    2.3.1 Aerosol optical depth .............................................. 16
    2.3.2 HYSPLIT ............................................................. 19
  2.4 Results and discussion ................................................... 19
    2.4.1 HMS Satellite Fire Detection ...................................... 19
    2.4.2 HYSPLIT trajectories ................................................ 25
    2.4.3 Forest fire case study, July-August 2009 ...................... 27
  2.5 Conclusions .............................................................. 37

3 Forest fire impacts on PM$_{2.5}$ and O$_3$ concentrations ........ 39
  3.1 Introduction .............................................................. 39
  3.2 Background ............................................................... 40
    3.2.1 Meteorology and pollutant concentrations .................... 40
    3.2.2 Sources and sinks of PM$_{2.5}$ and O$_3$ in the Georgia Basin airshed ............................................. 41
    3.2.3 Synoptic typing classification ................................... 42
  3.3 Methods ................................................................. 44
    3.3.1 Data ................................................................. 44
  3.4 Results and discussion ................................................... 47
    3.4.1 Identification of smoke and non-smoke days ............... 47
    3.4.2 Particulate matter .................................................. 51
    3.4.3 Ozone ............................................................... 58
  3.5 Conclusions .............................................................. 63
4 Atmospheric visibility using digital images .............................................. 66
    4.1 Introduction ................................................................. 66
    4.2 Background ................................................................. 67
        4.2.1 Atmospheric visibility .............................................. 67
        4.2.2 KatKam images ....................................................... 67
    4.3 Methods ...................................................................... 69
    4.4 Results and discussion .................................................... 75
    4.5 Conclusions ................................................................. 79

5 Conclusion .............................................................................. 81
    5.1 Summary of results .......................................................... 81
    5.2 Future research outlook ..................................................... 85

Bibliography ................................................................. 87
List of Tables

Table 1.1  Data analysis methods and data set information . . . . . . . . . [10]
Table 2.1  Average precipitation and temperature anomalies for the Pacific Coast of British Columbia from 2008-2011. . . . . . . . . [15]
Table 2.2  Area burned (hectares) and total number of forest fires along the coast of western North America from 2008-2011. . . . . . . . [21]
Table 2.3  Smoke days from 2008-2011 classified using Satellite Fire Detection . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . [24]
Table 2.4  Percent of cross-border transport of air on smoke days. . . . [27]
Table 3.1  PM$_{2.5}$ and O$_3$ monitor locations analyzed across the Georgia Basin. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . [46]
Table 3.2  Comparison of particulate matter concentrations by station during smoke and non-smoke events . . . . . . . . . . . . . . [57]
Table 3.3  Comparison of ozone concentrations by station during smoke and non-smoke events . . . . . . . . . . . . . . . . . . . . . [62]
Table 4.1  Correlation values for the comparison of the actual observed extinction to the estimated extinction at each target and p-values along with Root Mean Square Error for each target. . . . . . . [75]
# List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1.1</td>
<td>Map of the Georgia Basin/ Puget Sound airshed study area</td>
<td>9</td>
</tr>
<tr>
<td>Figure 2.1</td>
<td>HMS Satellite Fire Detection (SFD) imagery from 03 August 2010</td>
<td>16</td>
</tr>
<tr>
<td>Figure 2.2</td>
<td>Map showing the location of the sunphotometer on Saturna Island</td>
<td>17</td>
</tr>
<tr>
<td>Figure 2.3</td>
<td>AOD fine and coarse mode optical depths during August 2008 smoke event</td>
<td>18</td>
</tr>
<tr>
<td>Figure 2.4</td>
<td>Satellite Fire Detection imagery on 05 August and 06 August 2008</td>
<td>22</td>
</tr>
<tr>
<td>Figure 2.5</td>
<td>Satellite Fire Detection imagery on 02 August and 03 August 2010</td>
<td>23</td>
</tr>
<tr>
<td>Figure 2.6</td>
<td>HYSPLIT back-trajectories grouped by year</td>
<td>25</td>
</tr>
<tr>
<td>Figure 2.7</td>
<td>Weather maps at the surface and 500 mb on 29 July and 30 July 2009</td>
<td>28</td>
</tr>
<tr>
<td>Figure 2.8</td>
<td>HYSPLIT back-trajectory from smoke event in July 2009</td>
<td>29</td>
</tr>
<tr>
<td>Figure 2.9</td>
<td>SFD imagery from 28 July 2009 and HYSPLIT trajectory 28 July 2009</td>
<td>31</td>
</tr>
<tr>
<td>Figure 2.10</td>
<td>Aerosol Optical Depth during 27 July- 05 August, 2009 Smoke Event</td>
<td>33</td>
</tr>
<tr>
<td>Figure 2.11</td>
<td>Lidar images from UBC 27 July through 06 August 2009</td>
<td>35</td>
</tr>
<tr>
<td>Figure 2.12</td>
<td>Particulate matter and ozone concentrations at Vancouver International Airport (YVR) from 24 July through 05 August 2009</td>
<td>36</td>
</tr>
<tr>
<td>Figure 2.13</td>
<td>KatKam images during the smoke event on 30 July 2009</td>
<td>37</td>
</tr>
</tbody>
</table>
Figure 3.1 Synoptic weather typing classification .................................. 43
Figure 3.2 PM$_{2.5}$ and O$_3$ monitor locations across the Lower Fraser Valley (LFV) ................................................................. 45
Figure 3.3 Frequency distribution of smoke and non-smoke days using a Principal Component Analysis (PCA) based weather type classification ............................................. 48
Figure 3.4 Frequency distribution of synoptic weather types on all non-smoke summer days compared to smoke days. ................. 49
Figure 3.5 Weather map for weather type 5 ........................................... 50
Figure 3.6 Weather map for weather type 7 ........................................... 51
Figure 3.7 Comparison of PM$_{2.5}$ during smoke and non-smoke events at eight different monitors across the LFV. ......................... 54
Figure 3.8 PM$_{2.5}$ comparison during smoke and non-smoke events at four monitors across the Georgia Basin airshed ...................... 56
Figure 3.9 Comparison ozone during smoke and non-smoke events at eight different monitors located across the LFV. ....................... 59
Figure 3.10 Comparison of ozone during smoke and non-smoke events ........ 61
Figure 3.11 O$_3$ and PM$_{2.5}$ impacts on air quality. ............................. 63

Figure 4.1 Example of a KatKam image, 03 June 2009 at 12 pm. ......... 68
Figure 4.2 View of the KatKam camera ................................................. 71
Figure 4.3 Target locations and distance from KatKam camera. ........... 72
Figure 4.4 Estimated extinction from the Bowen Island target compared to observed extinction in Abbotsford, British Columbia. .... 77
Figure 4.5 Comparison of smoke and non-smoke days from the 2009 fire season with calculated extinction and visual range values for each day. ...................................................... 79
## Glossary

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AOD</td>
<td>Aerosol Optical Depth</td>
</tr>
<tr>
<td>CWS</td>
<td>Canada Wide Standards</td>
</tr>
<tr>
<td>HMS</td>
<td>Hazard Mapping Systems</td>
</tr>
<tr>
<td>DEM</td>
<td>Digital Elevation Model</td>
</tr>
<tr>
<td>LFV</td>
<td>Lower Fraser Valley</td>
</tr>
<tr>
<td>NCEP</td>
<td>National Centers for Environmental Protection</td>
</tr>
<tr>
<td>NGDC</td>
<td>National Geophysical Data Centre</td>
</tr>
<tr>
<td>NOAA</td>
<td>National Oceanic and Atmospheric Administration</td>
</tr>
<tr>
<td>PCA</td>
<td>Principal Component Analysis</td>
</tr>
<tr>
<td>PM</td>
<td>Particulate Matter</td>
</tr>
<tr>
<td>SFD</td>
<td>Satellite Fire Detection</td>
</tr>
<tr>
<td>TSI</td>
<td>Telemark Systems Incorporated</td>
</tr>
<tr>
<td>UTM</td>
<td>Universal Transverse Mercator</td>
</tr>
<tr>
<td>YVR</td>
<td>Vancouver International Airport</td>
</tr>
</tbody>
</table>
Acknowledgments

I would like to thank my supervisor Dr. Ian McKendry, for all of his guidance and patience with me over the last two years. His advice and positive encouragement helped me an enormous amount along the way. I would also like to thank the members of my committee, Dr. Simon Donner and Dr. Dan Moore for their feedback and assistance. The R community in UBC Geography especially Dr. Dan Moore who helped me get my code running. I would like to say thank you to all of my fellow graduate students in the Geography Department at UBC, the support and environment made it a great place to work and learn. Especially, Sandra Banholzer, my good friend, who always encouraged and supported throughout the last two years. Also I need to thank my family who has encouraged and has always been there for me throughout my academic career. And special thanks goes to James, who has continuously supported and help me through this adventure.

Furthermore, this research would not have been possible without the support of those at Environment Canada in Vancouver. I would like to acknowledge Andrew Teakles, who spent many days over the summer helping me get my visibility scripts up and running. Additionally, Rita So was a great help providing data and assistance with coding the visibility work. Keith Jones, who helped me acquire particulate matter and ozone data. Along with all the other individuals at Environment Canada who took part in the data collection across the LFV.

Additionally, I gratefully acknowledge the NOAA Air Resources Laboratory (ARL) for the provision of the HYSPLIT transport and dispersion model and/or READY website (http://ready.arl.noaa.gov) used in this research. Along with those at NOAA who are a part of the Satellite Services Division.
Chapter 1

Introduction

1.1 Motivation for study

Climate change scenarios suggest the frequency and severity of forest fires will increase in western North America over the next century (Jaffe et al., 2008a, Innes et al., 2009). With an increase in forest fire activity, recent research has investigated the impacts forest fire smoke has on air quality and visibility (Pahlow et al., 2005, Jaffe et al., 2008b). Fine soot particles generated from forest fires can travel over long distances, degrading air quality. Poor air quality has economic, health and aesthetic impacts. With our changing climate, forest fires are projected to increase (Jaffe et al., 2008b). Climate change has been linked to increasing forest fires due to the increasing spring and summer temperatures, earlier snowmelt and dryer conditions (Jaffe et al., 2008a). Climate models have projected an increase in frequency of forest fires in western North America as well as an increase in area burnt by forest fires (Innes et al., 2009). With the projected increase in forest fires in Canada and the western United States it is important to better understand the role forest fires play on air quality and haze (Jaffe et al., 2008b).

In this study, the impacts of forest fire smoke on concentrations of fine particulate matter (PM$_{2.5}$), ozone (O$_3$) and visibility in the Georgia basin region were examined during forest fire smoke events from 2008-2011. The overall goal of this research is to improve the understanding of the role forest fires have on air quality within the Lower Fraser Valley (LFV). Forest fires are significant sources of gases
and aerosols (Jaffe et al., 2008b). Gases and aerosols emitted from forest fires can have negative health impacts on vulnerable individuals such as children and the elderly. Particulate matter which is produced during forest fires is known to penetrate deep into the lungs and cause respiratory and cardiovascular illnesses (EPA, 1996). Particulate matter can exist in the atmosphere for days or weeks and can be transported thousands of miles affecting visibility locally, regionally, and globally (Hyslop, 2009).

As the frequency of forest fires continues to increase with our changing climate, it is important to understand how the smoke from forest fires influences air quality in the Georgia Basin/Puget Sound airshed. While there have been numerous studies investigating the transportation of forest fire smoke and impacts on air quality in areas such as Los Angeles and eastern Canada, there is a significant need for this research within British Columbia. The Georgia Basin/Puget Sound airshed is of significant interest as the region is prone to long-range transport of aerosols from Asia and regional transport from western North America. This study investigates air quality and visibility during the months of April through October from 2008 through 2011. Determining the relationship between forest fire smoke, PM$_{2.5}$ and O$_3$ concentrations and air quality will improve air quality predictions and our understanding of air pollution produced by forest fires. Results from this research give insight into broader issues such as the transportation of aerosols and air quality management.

1.2 Project description

Numerous studies have examined the transport of dust to southwest British Columbia (McKendry et al. (2001), Jaffe et al. (2003)) but there has been little research on the influence of forest fire smoke on air quality (McKendry et al. (2011b), Jaffe et al. (2008b)). Although there have been a few studies examining the transport of aerosols from forest fires in southwestern British Columbia, there is a further need to quantify the relationship between smoke, air quality and visibility. To assist in understanding the influence of forest fire smoke on air quality and visibility the objectives of this research are:

1. To determine the source of the majority of pollutants in the LFV.
2. To examine whether there is interannual variability in PM$_{2.5}$ and O$_3$ levels during forest fire smoke events.

3. To examine the extent to which forest fire smoke impacts air quality and visibility.

4. To automate the calculation of visibility using digital images.

5. To determine how visibility is degraded during forest fire smoke events.

1.3 Background and methods

1.3.1 Frequency of forest fires in western North America

In Canada, forests cover approximately 45 percent of the land, and forest fires burn millions of acres annually (Skinner et al., 1999) and forest fires produce large amounts of haze and smoke with substantial horizontal and vertical transport (Forster et al., 2001). Additionally, forest fires can be significant economic and environmental hazards (Skinner et al., 1999). It has been determined that weather and climate, fuels and human activity have the largest influence of forest fires in Canada (Flannigan and Wotton, 2001; Flannigan et al., 2005; Hely et al., 2001). In particular, weather influences forest fires as it impacts fuel moisture, lightning strikes, and fire growth/spread caused by wind (Flannigan et al., 2005). Hot, dry summers which occur in western North America make this region prone to large forest fires (Jaffe et al., 2008b). Various studies have examined the smoke transport from forest fires in western North America. Forest fires play a significant role in regional haze events in western states and increase concentrations of PM$_{2.5}$ (Jaffe et al., 2008b). For example, it was found that during large fire seasons, there were seasonal increases in PM$_{2.5}$ (Jaffe et al., 2008b). The frequency of forest fires in British Columbia varies annually, it is important to determine how much smoke from forest fire influences air quality (Jaffe et al., 2008b). Also, during a large fire season in 2008, McKendry et al. (2011b) observed two significant events in which aerosols were transported from forest fires in northern California and Oregon to southwestern British Columbia.
1.3.2 Long-range transport of pollutants

Pollutants such as PM$_{2.5}$ and O$_3$ can travel hundreds of kilometers from the location of the fire, negatively influencing air quality in urban areas (Sapkota et al., 2005; Pahlow et al., 2005). Wiedinmyer et al. (2006) suggests that the transport of gases and aerosols through the atmosphere produce harmful concentrations of PM$_{2.5}$ and O$_3$ along with significantly degrading visibility. It has been determined that smoke plumes can cause regional haze events at great distances from the location of the fire where air quality impacts can be visually assessed (Patterson and McMahon, 1984). Southwestern British Columbia has experienced regional transport events from forest fires located in California and Oregon which have been investigated by McKendry et al. (2011b). Aside from the transport of smoke from forest fires, the coast of western North America also experiences elevated concentrations of particulate matter due to dust transported across the Pacific from China (McKendry et al., 2001).

1.3.3 Biomass burning and smoke properties

Biomass burning has various impacts on our atmospheric chemistry. Globally, biomass burning is thought to be the largest source of accumulation mode particles (Reid et al., 2005). Additionally, smoke particles produced by biomass burning are known to scatter and absorb solar radiation (Reid et al., 2005). The physical, optical and chemical properties of biomass burning were reviewed extensively by Reid et al. (2005) and Reid et al. (2005b). It has been determined that each fire is different and depends on fuel type, moisture, combustion phase and wind conditions to determine the properties of smoke (Reid et al., 2005). Biomass burning is a major source of air pollution and the second largest source of anthropogenic aerosols (IPCC, 2007). Forest fires increase concentrations of gases and aerosols in the atmosphere, including carbon dioxide (CO$_2$), carbon monoxide (CO), oxides of nitrogen (NO$_x$), volatile and semi-volatile organic compounds (VOC and SVOC), particulate matter (PM), ammonia (NH$_3$), sulphur dioxide (SO$_2$), and methane (CH$_4$) (Wiedinmyer et al., 2006). Jaffe et al. (2008a) has shown that emissions produced by forest fires depend on the surrounding ecosystem and the stage of the fire. Forest fire smoke plumes containing hot gases are known to penetrate into the
mixed layer (Sapkota et al., 2005). Smoke produced by forest fires also affects the radiative and reflective properties within the atmosphere (Forster et al., 2001). Determining the exact composition can be difficult as the composition of the particle depends on the condition of the burn, along with the atmospheric conditions at the time (Hudson et al., 2004).

1.3.4 Particulate matter and ozone

Particulate matter from biomass burning directly impacts visibility and air quality. There are numerous examples of air quality being influenced by particulate matter and other gases which have been transported over long-distances from forest fires (Jaffe et al., 2008b). The research conducted in relation to particulate matter usually includes studies examining both PM$_{10}$ and PM$_{2.5}$. Particulate matter is composed of solid or liquid particles and aerosols (Hyslop, 2009). PM$_{10}$ refers to particles with a diameter less than 10 microns, which are considered coarse. PM$_{2.5}$ refers to particles with a diameter less than 2.5 microns, which are referred to as fine particles. Fine particulate matter is produced from various natural and anthropogenic sources at the surface (McKendry and Lundgren, 2000). PM$_{2.5}$ and O$_3$ are known to vary diurnally, seasonally and annually. Amounts of PM$_{2.5}$ created from the fire depend on the duration and size of the fire, along with the burning conditions (Jaffe et al., 2008b). Particulate matter produced by forest fires can be easily transported across large regions and can affect visibility and health (Pahlow et al., 2005). Synoptic weather patterns play a significant role on pollutant concentrations (such as PM$_{2.5}$ and O$_3$) at the surface (Yarnal, 1993). On a local scale, dramatic and short-term increases of PM$_{2.5}$ concentrations have been seen due to biomass burning (Jaffe et al., 2008b). Furthermore, during longer fire seasons, greater seasonal increases in PM$_{2.5}$ have been observed in large regions (Jaffe et al., 2008b).

O$_3$ is formed through a photochemical reaction between sunlight and precursors such as NO$_x$ and VOCs (Yarnal, 1993). Additionally, Yarnal (1993) emphasizes it is important to understand that O$_3$ severely impacts human health and vegetation. Meteorology plays a large role on O$_3$ concentrations. For instance anti-cyclonic summertime conditions are known to produce photochemical smog (McKendry and Lundgren, 2000). Ground-level O$_3$ also follows a diurnal pattern,
with concentrations increasing after sunrise throughout the day and decreasing after sunset. Jaffe et al. (2008a) investigated the relationship between forest fires and concentrations of O$_3$ in the western United States and found that the presence of forest fire smoke plays a larger role on concentrations of O$_3$ than temperature.

1.3.5 Canada wide standards for particulate matter and ozone

In Canada, standards set to regulate ground level concentrations of Particulate Matter (PM) and O$_3$ were established in June of 2000 (CCME, 2000). Canada Wide Standards were created to help monitor and regulate pollutants to meet air quality standards. For example, for PM$_{2.5}$ the Canada Wide Standard is 30 µgm$^{-3}$ based on a 24 hour rolling average (CCME, 2000). The CCME (2000) also states that the achievement is based on the 98th percentile ambient measurement annually, averaged over three consecutive years. Further, the CCME (2000) also states standards for O$_3$, 8 hour rolling averages must not exceed the Canada Wide Standard of 65 ppb. Additionally the achievement is based on the 4th highest measurement annually, averaged over three consecutive years. Canada Wide Standards were set to assist in achieving long-term goals of reducing health risks and negative environmental impacts associated with poor air quality. The Canada Wide Standards for air quality are somewhat similar to the regulations set by the United States Environmental Protection Agency (EPA). National standards for PM$_{2.5}$ and O$_3$ set by the US EPA are stricter than those in Canada by 5 µgm$^{-3}$ for PM$_{2.5}$ and 5 ppb for O$_3$. In this research these standards are used as a basis for examining the impacts of forest fire smoke on air quality and visibility.

1.3.6 Health impacts related to particulate matter and ozone

Particulate matter has been linked to negative health outcomes. Increased exposure to PM$_{2.5}$ can penetrate deep into the lungs and cause lung and respiratory diseases (Wang and Christopher, 2003; Al-Saadi et al., 2005). Communities which are exposed to smoke from forest fires have seen increased emergency room and hospital admissions for chronic obstructive pulmonary disease, bronchitis, and asthma and chest pain (Mott et al., 2002). Henderson et al. (2011) determined that increased levels of PM$_{10}$ in Kelowna, British Columbia produced by forest fires increased
visits to the doctor due to respiratory illnesses. Additionally, it has been determined that PM$_{2.5}$ experiences the greatest increases during fire events and it is also associated with various negative health impacts (Wu, 2006). A study conducted by Mott et al. (2002) found that there were less adverse health impacts reported during smoke events when public service announcements were made. Transport of fine particulate matter indoors is an issue, due to the large amount of time the average person spends indoors (Sapkota et al., 2005).

High concentrations of ozone have also been associated with negative health impacts. Ebi and McGregor (2008) have shown that ground-level O$_3$ affects respiratory membranes, lung tissues and respiratory function. Some of the short-term negative impacts of high concentrations of O$_3$ include increased daily deaths and hospital admissions during summer months (Katsouyanni, 2003). Along with increased respiratory illnesses, changes in pulmonary function and airway inflammation are common (Katsouyanni, 2003).

### 1.3.7 Atmospheric visibility

This section provides an overview of the use of digital images to calculate visibility. A detailed description of the methods used for this research are described in Chapter 4. Hyslop (2009) defines visibility as ‘the clarity or transparency of the atmosphere and the associated ability to see distant objects.’ In addition, PM significantly impacts visibility, as it accumulates and causes haze (Hyslop, 2009). Further, PM affects visibility in a variety of different ways: the particles scatter light coming from an object which diminish contrast, absorb light giving a grayish colour and scatter sunlight which subdues colour (Hyslop, 2009). Patterson and McMahon (1984) emphasizes the importance of predicting visibility reduction from forest fire smoke. Aerosol loading, atmospheric chemistry and humidity influence visibility (Jaffe et al., 2008b). Humidity plays a role in visibility as humidity creates larger particles which scatter more light than dry particles (Janeiro et al., 2003). Degraded visibility is the most obvious sign of air pollution and can negatively impact tourism, as it influences how we perceive the landscape and scenery surrounding us (Hyslop, 2009).

Originally, visibility was determined by human observers, who estimated vi-
visual range using objects or landmarks at known distances. Visual range is the longest distance at which landmarks are still visible, and depends on the humidity and the concentration of particles in the air (Hyslop, 2009). Dark objects in the distance can be used to calculate visibility (Janeiro et al., 2003). More recently, nephelometers have been used to calculate atmospheric extinction. The extinction coefficient is a measure of light transmission between an observed and a object, taking into account the scattering and absorption of light (Janeiro et al., 2003). From the observed extinction values, visual range (VR) can be calculated using Koschiemder’s visibility formula which is:

\[ VR = -\ln(\text{CL})/b_{\text{ext}} \]  

(1.1)

VR and \( b_{\text{ext}} \) (extinction) are inversely related and CL is the minimum observed contrast. During Rayleigh scattering, in a clean atmosphere visual range has been observed over 350 km (Hyslop, 2009). Currently, nephelometers are instruments which are used to monitor extinction. Aerosol Optical Depth (AOD) which is measured using a sunphotometer determines how much small particles affect the transmission of sunlight through the atmosphere. An alternative method to using ground-based instruments is to calculate visibility using digital images which is described in Chapter 4.

1.4 Study area description

The scope of this study looks at the Georgia Basin/Puget Sound airshed, roughly covering a region which lies within 126°W-120°W 45°N-54°N and focuses particularly on the LFV (Figure 4.1). The Georgia Basin/Puget Sound airshed is an international airshed made up of two smaller airsheds, and spans across the coastal region of the Canada-USA boarder. Large cities such as Vancouver, British Columbia and Seattle, Washington lie within the region. Thomson and Yukon Region (2004) suggested that the term “airshed” is usually defined similar to nearby watersheds. For the proposed research the Georgia Basin is defined by the watershed of the Strait of Georgia. The Georgia Basin experiences air pollution from a variety of sources, including marine vessels, vehicles, agriculture, industrial combustion and thermal power plants (Thomson and Yukon Region, 2004). During the summer
months the LFV experiences poor air quality due to the buildup of pollutants during anti-cyclonic conditions (McKendry, 2000). To fully understand the influence of forest fire smoke in the region, PM$_{2.5}$ and O$_3$ are thoroughly investigated in later chapters.

Figure 1.1: Georgia Basin/Pudget Sound airshed. Source: Environment Canada, by permission.
1.5 Data analysis methods and data sets

A basic description of the data analysis methods and data sets used throughout this research are summarized in Table 1.1. A thorough description of the data sets utilized and methods used to analyze the data is given in the appropriate chapter. Historical temperature and precipitation data for southwest British Columbia were obtained from Environment Canada’s online archive (http://www.ec.gc.ca/adc-sc-cmda/). Fire history data for British Columbia was obtained from the Wildfire Management Branch of British Columbia and for the western United States it data were obtained from the National Interagency Fire Center.

Table 1.1: Data analysis methods and data set information.

<table>
<thead>
<tr>
<th>Data Analysis Method</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Satellite Fire Detection (SFD)</strong></td>
<td>Used SFD from National Oceanic and Atmospheric Administration (NOAA) to determine which days smoke affected the Georgia Basin airshed (<a href="http://www.firedetect.noaa.gov/viewer.htm">http://www.firedetect.noaa.gov/viewer.htm</a>).</td>
</tr>
<tr>
<td><strong>HYSPLIT</strong></td>
<td>HYSPLIT is a part of NOAA’s Air Resources Laboratory. Trajectories computed using EDAS meteorological data to determine the trajectory of air parcels on smoke days.</td>
</tr>
<tr>
<td><strong>Fire history data</strong></td>
<td>Area burned and total fires from <a href="http://www.nifc.gov/fireInfo/fireInfo_statistics.html">http://www.nifc.gov/fireInfo/fireInfo_statistics.html</a> and <a href="http://bcwildfire.ca/History/average.htm">http://bcwildfire.ca/History/average.htm</a></td>
</tr>
<tr>
<td><strong>PM$_{2.5}$ and O$_3$</strong></td>
<td>Hourly data from the B.C Ministry of Environment’s air quality monitoring network within the LFV were used to determine air quality impacts.</td>
</tr>
<tr>
<td><strong>KatKam imagery</strong></td>
<td>Digital images from <a href="http://www.katkam.ca">www.katkam.ca</a> by permission were used to determine visibility.</td>
</tr>
</tbody>
</table>
1.5.1 Quality control

Prior to detailed analysis the data sets were all manually checked for consistency and overall quality. Only a general analysis of data quality was conducted as most data is quality assured by the governing institution. The first step was to check for missing data or gaps. A large part of the data used was collected on an hourly basis. Specifically, PM$_{2.5}$ and O$_3$ data were measured each hour at twelve different locations across southwestern British Columbia. Seven of the monitors out of thirteen had missing particulate matter data for a short period. Missing measurements were due to the instrument being down or re-calibrated. Data were also checked for extreme values or bad data. To check for extreme or bad values within the data, time series plots were created to determine the variations in concentrations. Digital images manually downloaded from [www.katkam.ca](http://www.katkam.ca) were also checked to ensure the best possible quality. The images were downloaded at 9 am, 12 pm and 3 pm for each day of the study period. Once all of the images were downloaded, before image registration the images were checked to make sure all of the targets in the scene were visible. Images in which the camera was covered by rain drops were deleted.

1.6 Project overview

This thesis is comprised of five chapters. Chapter 2 identifies days in which smoke plumes from forest fires are covering the Georgia Basin/Puget Sound airshed. Additionally, it investigates the transport of air on smoke days using HYSPLIT. Backward trajectories are computed to determine where air is being transported from on smoke days and if it crosses the Canada/US international border. After the transport of air on smoke days is examined, the impacts of PM$_{2.5}$ and O$_3$ are examined in Chapter 3. Concentrations of PM$_{2.5}$ and O$_3$ are examined at twelve different locations across the Georgia Basin airshed. Chapter 4 investigates how smoke produced by forest fires influences visibility in the LFV. Atmospheric visibility is examined using digital images taken in Vancouver, British Columbia. Finally, Chapter 5 summarizes all of the results and gives insight into future research relating to air quality and visibility within the Georgia Basin airshed.
Chapter 2

Satellite Fire Detection and HYSPLIT

2.1 Introduction
The objectives of this chapter are to identify days when forest fire smoke affected air quality in the LFV, and to determine the trajectories of air parcels on smoke days using HYSPLIT, negatively influencing air quality. Other objectives include examining the interannual variability of smoke transport and to describe a case study of forest fire smoke influencing air quality in the LFV. In this chapter, combinations of different tools were used to determine ”smoke” days and the trajectory of air parcels on ”smoke” days. NOAA’s SFD was used to determine smoke and non-smoke days during the months of April through October from 2008-2011. HYSPLIT trajectories were computed individually for each fire event and annually. HYSPLIT was also used to determine how much of the air on smoke days experienced cross border transport from the United States into Canada.
2.2 Background

2.2.1 HMS Satellite Fire Detection

In satellite fire detection (SFD), observations from a combination of different satellites are used to determine which regions are being influenced by smoke from forest fires. These satellite images are created by satellite image analysts who use a combination of the Automated Biomass Burning Algorithm (ABBA) and Geostationary Operational Environmental Satellites (GOES) to show the location of the fire and the smoke plume. Hazard Mapping Systems (HMS) Smoke and Fire product is also used in combination with the ABBA GOES products to create the Satellite Fire Detection imagery. NOAA has recently developed another fire product which is a part of NOAA’s Satellite and Information Service and it is has a simpler interface using an ArcIMS server. Different layers can be turned on and off and the user can choose different satellite images they would like to examine. In addition, there are now different layers for dense, moderately dense and thin smoke plumes as determined by the satellite imagery. NOAA (2009) states that the dense, moderately dense and thin classifications are to be used to differentiate between the different densities of smoke within a plume and to provide an estimate of the smoke concentrations in micrograms per cubic meter. The fire product from the Satellite and Information Service only displays data from the current and previous date, therefore the HMS archive was used. There are a few limitations to using the SFD images since the products are based on satellite imagery. For example, the presence of clouds can obstruct the view of smoke, smoke maybe present but may not appear in the final product. The thickness of the smoke or size of the smoke plume may not be recognized by the satellite if it falls below the satellite resolution. Lastly, SFD looks at the atmosphere from the top down, therefore it is not possible to determine at which level in the atmosphere the smoke is present. In this study, summer days in which smoke affected the Georgia Basin airshed were determined from 2008-2011. An example of an image showing smoke from forest fires over the Georgia Basin airshed is shown in Figure 2.1.
2.2.2 HYSPLIT

HYSPLIT (HYbrid Single-Particle Lagrangian Integrated Trajectory) modeling is used to examine air quality, deposition and the dispersion of pollutants through the atmosphere, by computing trajectories of air parcels in different scenarios (Draxler and Rolph, 2012). The two main HYSPLIT models used are the trajectory and dispersion models, which use archived data to compute the model runs. HYSPLIT modeling can be used to create backward and/or forward trajectories of particles, using meteorological data. The models combine both Lagrangian and Eulerian approaches. Lagrangian methods determine the advection and diffusion of the air parcel, using a moving frame of reference which tracks the air parcel from the starting point, while the Eulerian part of the model uses a 3-D fixed grid as a reference frame, in which pollutant concentrations are derived from NOAA. The results of HYSPLIT modeling allow for a better understanding of areas which are impacted by a release of chemicals into the atmosphere. HYSPLIT can be used to track volcanic ash, smoke from forest fires, hazardous chemical releases and pollutants from other sources. McKendry et al. (2011b) and Sapkota et al. (2005) both use HYSPLIT to track air parcels during forest fire smoke events. For the purpose of this research HYSPLIT was used to determine where air parcels originated from on each of the smoke days within the study period.

2.2.3 Synoptic weather patterns and yearly weather trends

The Georgia Basin airshed is situated within complex coastal terrain. During summer months in the LFV synoptic weather patterns play a significant role in modulating pollutant concentrations, specifically PM$_{2.5}$ and O$_3$. In addition, during times in which anti-cyclones stagnate over the region wind flow is decreased causing pollutants to build up in both the Georgia Basin Puget Sound airshed (Thomson and Yukon Region (2004), McKendry (2000)). Reduced circulation within the airsheds during the summer months can also lead to temperature inversions, significantly degrading air quality (Thomson and Yukon Region, 2004). Interannual variations in summer temperature and precipitation are factors which influence the frequency and severity of forest fires (Flannigan et al., 2005).

Temperature and precipitation averages for each summer 2008-2011 acquired
from Environment Canada are shown in Table 2.1, and compared with averages calculated for the summer months from 1984-2011. For precipitation, the percent depression of the average precipitation from 1984-2011 is shown. Rank reflects the wettest to driest summer from 1948-2011. On this basis, 2008 was the wettest summer for the four year study period. Of the four year study period, 2009 and 2010 were the driest summers. For temperature, the departure from the mean summer temperature from 1948-2011 is shown. Summer temperatures were warmest during 2009 and 2010. Rank of temperature reflects the warmest to coolest summers from 1984-2011. Overall, the summer of 2009 was the warmest and driest summer, and 2008 was the coolest and wettest summer. The summer of 2010 was dry with average temperatures, while 2011 experienced a wetter and cooler summer than usual.

Table 2.1: Average precipitation and temperature anomalies from the Pacific Coast of British Columbia from 2008-2011.

<table>
<thead>
<tr>
<th>Year</th>
<th>Avg. Precipitation</th>
<th>Avg. Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% Anomaly</td>
<td>Rank</td>
</tr>
<tr>
<td>2008</td>
<td>26</td>
<td>10th</td>
</tr>
<tr>
<td>2009</td>
<td>-39</td>
<td>62nd</td>
</tr>
<tr>
<td>2010</td>
<td>-32</td>
<td>59th</td>
</tr>
<tr>
<td>2011</td>
<td>-1</td>
<td>37th</td>
</tr>
</tbody>
</table>

2.3 Methods

SFD was used to determine smoke and non-smoke days. For the purpose of this study, smoke days are defined as days in which a smoke plume was shown to be covering the Georgia Basin airshed on the SFD imagery for a period of 24 hours. The smoke plume had to be covering the majority of the airshed to be considered a smoke day. Classification of smoke days was based on qualitative judgment. An example of the SFD imagery product displaying the location of the fire along with the smoke plume, as shown in Figure 2.1.
2.3.1 Aerosol optical depth

To confirm that the SFD was recognizing smoke, AOD was examined. Ground based remote sensing instruments make up AERONET (AErosol RObitic NETwork) (McKendry et al., 2011b). The monitors located within Canada are a part of the AEROCAN CIMELS network, which is a sub-network of AERONET (McKendry et al., 2011b). AOD data were acquired from the sunphotometer which is stationed on Saturna Island, located 50 km southwest of Vancouver (Figure 2.2). The network measures vertically integrated aerosol properties using a CIMEL sunphotometer/sky radiometer (McKendry et al., 2011b), (Eck et al., 2009). CIMEL sunphotometers transform solar radiances into three processing levels of AOD (1.0 non-cloud screened, 1.5 cloud screened and 2.0 cloud screened and quality assured) at eight different spectral channels (340, 380, 440, 500, 670, 870, 1020 and 1640nm) (McKendry et al., 2011b).

Figure 2.1: SFD imagery from 03 August 2010. The gray mask shows the extent of the observed smoke while the black squares show the location of the fires.
Figure 2.2: Location of the sunphotometer on Saturna Island and the location of PM$_{2.5}$ and O$_3$ monitors across the LFV.

For the purpose of this research the AOD was examined at 500 nm ($\tau_{500}$) split
into fine and coarse mode optical depths. The AOD was examined at 500 nm as it is the most accurate wavelength and is appropriate for this work. McKendry et al. (2011b) defines fine mode particles as particles usually associated with smoke or pollution and coarse mode particles are generally derived from mechanical processes such as abrasion and mobilization of soil and dust from the surface. Fine mode particles tend to be less than 2.5 microns in diameter while coarse mode particles are larger than 2.5 microns. Fine and coarse mode optical depths were pre-determined by Aero-CAN prior to download. For example, fine and coarse mode particles are examined during an August 2008 smoke event in Figure 2.3. The increase in fine mode particles (blue) on 06 August 2008 is indicative of the presence of forest fire smoke in the region. Examining the fine and coarse mode optical depths helps distinguish smoke based aerosols from other aerosol types dominating at $\tau_{500}$.

![Fine versus Coarse Mode](image)

**Figure 2.3:** AOD fine (blue) and coarse (red) mode 02 August to 12 August 2008.
2.3.2 HYSPLIT

HYSPLIT was used to compute backward trajectories from Vancouver International Airport (YVR). The trajectories were computed backward for 72 hours starting at 000Z on each smoke day. The backward trajectories display where the air parcels were transported from in each run, at different levels of the atmosphere. Backward trajectories were computed on each smoke day for 72 hours at 500 m, 1000 m and 2000 m A.G.L, the heights best represent air pollution transport events, which is usually at heights above the inversion layer (Sapkota et al., 2005). The trajectories were also created for each smoke day individually at 500 m to determine if the air parcel crossed the Canada-US international border. For the single particle backward trajectories a height of 500 m was chosen as HYSPLIT is not as accurate at lower altitudes due to the decreased resolution (Sapkota et al., 2005) and the model does not take into account the complex mountainous terrain. In addition to individual trajectories, trajectories were also grouped by smoke events to track the movement of the air parcels during specific smoke events. Backward trajectories were also grouped by year to determine any annual patterns during smoke events. HYSPLIT trajectories were compared to the satellite imagery saved from the SFD to compare smoke plumes and trajectories.

Eta Data Assimilation Systems (EDAS) 40 km meteorological data which is a part of the National Weather Service’s National Centers for Environmental Protection (NCEP) was used to compute backward trajectories using HYSPLIT. EDAS data were produced by assimilating observations and radar data into 3 hour forecasts. EDAS meteorological data is most commonly used for air quality and dispersion modeling purposes. The data contains the basic fields that are u- and v-wind components, temperature and humidity.

2.4 Results and discussion

2.4.1 HMS Satellite Fire Detection

It was determined that there was a total of 77 smoke days from 2008 through 2011, after examining the HMS for each day of the study period (Table 2.3). The summer of 2009 had the most smoke days with a total of 30. During the summer months in
2009, smoke days accounted for 30% of the summer days. The number of smoke days varied each year. The fire summer of 2008 experienced 20 smoke days and 2010 experienced 16 smoke days.

The number of smoke days observed each summer was consistent with the climatological patterns identified in Table 2.1. The warmest and driest summer was 2009, which also experienced the greatest number of smoke days. In addition to the greatest number of smoke days, in British Columbia the greatest number of forest fires was recorded in 2009. Cool and wetter than average summers were experienced in 2008 and 2011. The summer of 2008 still experienced a significant number of smoke days, which were due to transport of smoke from the United States.

In British Columbia, 2010 had the greatest area burned with a total of 333,108 hectares, which is the combination of forest fires created by people and lighting (Table 2.2). Furthermore, the large area burned in British Columbia during 2010 also relates to the SFD imagery which shows almost all of the fires originating within British Columbia. The largest area burned in California and Washington was during 2008 as shown in Table 2.2. SFD imagery from the 2008 fire season shows the majority of the smoke plumes from California, Oregon and Washington covering southwestern British Columbia. An example of a transport event during 2008 is shown above in Figure 2.4.
Table 2.2: Area burned (hectares) and total number of forest fires along the coast of western North America from 2008-2011. From the Wildfire Management Branch of British Columbia and the National Interagency Fire Center.

<table>
<thead>
<tr>
<th>Year</th>
<th>BC Area</th>
<th>BC Total</th>
<th>WA Area</th>
<th>WA Total</th>
<th>OR Area</th>
<th>OR Total</th>
<th>CA Area</th>
<th>CA Total</th>
<th>Total Area</th>
<th>Total Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>13,240</td>
<td>2,023</td>
<td>59,595</td>
<td>1,303</td>
<td>55,268</td>
<td>1,766</td>
<td>542,213</td>
<td>5,812</td>
<td>670,316</td>
<td>10,904</td>
</tr>
<tr>
<td>2009</td>
<td>247,419</td>
<td>3,064</td>
<td>31,261</td>
<td>1,976</td>
<td>40,738</td>
<td>1,488</td>
<td>406,134</td>
<td>9,159</td>
<td>483,552</td>
<td>15,687</td>
</tr>
<tr>
<td>2010</td>
<td>333,108</td>
<td>1,673</td>
<td>16,653</td>
<td>888</td>
<td>28,175</td>
<td>1,299</td>
<td>44,006</td>
<td>6,502</td>
<td>421,942</td>
<td>10,362</td>
</tr>
<tr>
<td>2011</td>
<td>NA</td>
<td>NA</td>
<td>6,264</td>
<td>993</td>
<td>113,986</td>
<td>1,151</td>
<td>52,616</td>
<td>7,989</td>
<td>172,866</td>
<td>10,133</td>
</tr>
</tbody>
</table>
Forest fire smoke was transported from fires located in Alberta, northern British Columbia and parts of the western United States to the Georgia Basin from 2008-2011. Specifically during the 2008 fire season, the majority of fires took place in California and Oregon and the forest fire smoke was transported to southwestern British Columbia (Figure 2.4). The forest fire that took place in northern California from 05 August to 08 August is represented with yellow squares and the smoke plume extending northward into British Columbia.

Figure 2.4: Satellite Fire Detection imagery on 05 August and 06 August 2008. Showing fires located in California and Oregon with smoke being transported northward to southwestern British Columbia.

During the fire season of 2010 southwestern British Columbia experienced numerous smoke events from forest fires located in northern British Columbia. The majority of the forest fires were located northeast of the Vancouver area. For example, a smoke event took place from 31 July to 06 August 2010 in which the fires were located in northern British Columbia, in the Williams Lake area. Figure 2.5 shows the SFD imagery for 02 August and 03 August 2010. Smoke plumes shown in Figure 2.5 are very thick, but fires can be seen to the north on 02 August 2010.
AOD was used to confirm that the SFD was showing smoke present in the study area. From the investigation of the AOD during smoke events, it was confirmed that there was an increase in fine-mode optical depths during the smoke events determined through SFD. For example, during the smoke event that took place from 05 August 2008 to 08 August 2008 shown in Figure 2.3, the AOD fine mode optical depth reached a maximum of 0.41 nm on 06 August 2008. Figure 2.3 shows the fine and coarse mode particles before and after the smoke event that took place from 05 August to 08 August. Late on 06 August there is an increase in the fine mode particles which continues until the beginning of 09 August, which is when the SFD detected forest fire smoke in the region. During the August 2008 smoke event it is apparent that fine mode particles are dominating at $\tau_{500}$. 

Figure 2.5: Satellite Fire Detection imagery on 02 August and 03 August 2010.
**Table 2.3:** Smoke days from 2008-2011 classified using Satellite Fire Detection

<table>
<thead>
<tr>
<th>Month</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>April</td>
<td>24, 25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>May</td>
<td></td>
<td></td>
<td></td>
<td>18, 19, 28, 29</td>
</tr>
<tr>
<td>June</td>
<td>29, 30</td>
<td>1, 2, 3, 4, 5, 6, 7, 8, 9, 10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>July</td>
<td>1, 2, 6, 7, 8</td>
<td>11, 12, 21, 24, 25, 27, 28, 29, 30, 31</td>
<td>31</td>
<td>25, 27</td>
</tr>
<tr>
<td>August</td>
<td>5, 6, 7, 8, 16</td>
<td>1, 2, 3, 5, 18, 19, 29, 30, 31</td>
<td>1, 2, 3, 4, 5, 6, 13, 14, 15, 16, 17, 18, 24</td>
<td></td>
</tr>
<tr>
<td>September</td>
<td>15, 16, 17, 18, 19, 29</td>
<td>22</td>
<td>29, 30</td>
<td>7, 8, 10, 11, 12</td>
</tr>
<tr>
<td>October</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
2.4.2 HYSPLIT trajectories

Each of the fire seasons was examined individually to determine interannual variations (Figure 2.6). Depending on the location of the fire, smoke traveled anywhere from 50-1000 km to Vancouver in some instances. During the 2008 fire season, it was determined that there were 20 smoke days. The majority of the smoke days were in July, August and September and were caused by the regional transport of smoke. As seen in the top left of Figure 2.6 the majority of the air parcels were transported from the south (United States), or originated west of Vancouver. Out of the 77 total smoke days from 2008 to 2011, on smoke day’s 40% of the time air parcels were transported across the Canada-US border. Table 2.4 displays the percent of air transported across the Canada-United States international border during each year of the study period on smoke days. A study by McKendry et al. (2011b) investigated smoke events from northern California and Oregon in which the smoke was transported to southwestern British Columbia during the summer of 2008, also used SFD, HYSPLIT and AOD to examine the transport of smoke.

During the 2009 fire season, there were 30 smoke days identified in southwestern British Columbia. Out of the four year study period, the fire season of 2009 experienced the most smoke days, and was also the driest and warmest of the four years (Table 2.1). It was determined from the HYSPLIT trajectories that the majority of the air parcels in 2009 arrived at Vancouver International Airport from the north, originating in northern British Columbia. On the top right of Figure 2.6 the HYSPLIT back-trajectories from 2009 are displayed, showing the majority of the air parcels in Vancouver originating from the north or west.

In 2010 southwestern British Columbia experienced a slow fire season until the end of July. The interior of British Columbia had numerous fires during late July and August of 2010. HYSPLIT back-trajectories show a significant number of trajectories air descending into Vancouver from the interior of British Columbia (Figure 2.6). The summer of 2010 was hot and dry making the region more susceptible to forest fires. During the 2010 fire season all of the trajectories on smoke days originated within Canada or off the west coast of Canada as shown in the bottom left of Figure 2.6.

The fire season of 2011 had the fewest number of smoke days, with a total of 11. Southwestern British Columbia experienced a cold and wet summer due to La Niña conditions. During the summer of 2011, 82% of the air parcels on smoke
days originated within Canada. HYSPLIT showed the air parcels to be coming from the west into Vancouver during smoke events as shown in the bottom right of Figure 2.6.

Up to 60% of the air on smoke days was transported to Canada from the south (from fires located in the United States). Most of the smoke which was transported across the Canadian-US border in 2008 originated in the United States of America, which is consistent with fire frequencies (Table 2.2). In addition, during 2009, 40% of the air parcels on smoke days were transported within the international airshed from the south and moved northward into Canada.

**Table 2.4:** Percent of air transported which experienced cross-border transport from the United States into Canada on smoke days.

<table>
<thead>
<tr>
<th>Year</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>60%</td>
<td>40%</td>
<td>25%</td>
<td>27%</td>
</tr>
</tbody>
</table>

The Georgia Basin airshed is prone to long-range transport of pollutants from Asia and different parts of western North America. Since the back-trajectories were run back for 72 hours, it was difficult to determine exactly where the air parcels originated on each of the smoke days as the back-trajectories were too short.

### 2.4.3 Forest fire case study, July-August 2009

In this section, a case study is presented to illustrate the meteorology, transport and air quality impacts of a large forest fire smoke event that took place from the end of July into early August of 2009. This smoke event was chosen as a case study as it was the longest smoke event and featured the worst air quality within the four year study period. Further, the synoptic weather pattern that dominated this event rarely happens in Vancouver and is likely to produce forest fires and is expected to occur more frequently in the future. The smoke event began on 27 July 2009 and ended on 05 August 2009. SFD showed smoke plumes covering southwestern British Columbia on each day of the smoke event. This smoke event The SFD imagery for 28 July 2009 showed that there were forest fires located 400-500km north of Vancouver and the smoke plumes covered the Georgia Basin/Puget Sound
Synoptic weather patterns play a significant role in the transport and dispersion of pollutants throughout the atmosphere. Figure 2.7 shows the weather patterns at the surface and 500 mb on 29 July 2009 and 30 July 2009 during the smoke event. At 500 mb a ridge of high pressure was present over British Columbia on both days, with low pressure moving in from the north on 30 July 2009. At the surface, a thermal trough was influencing the surface on both 29 July and 30 July which brought warm conditions and flow from the interior to the coast, usually associated with poor air quality (McKendry et al., 1997). High pressure is moving in from the north and bringing clear skies to the Georgia Basin airshed. Additionally, on 29 July 2009 a high temperature of 33.7°C and 33.9°C on 30 July 2009 was recorded. Predominant winds were coming from the northeast.

Figure 2.7: Weather maps at the surface and 500 mb on 29 July and 30 July 2009.

Smoke days were examined individually and by event using HYSPLIT. The trajectories were also computed at three different levels of the atmosphere. Fig-
Figure 2.8 displays back-trajectories for three days of the smoke event from 27 July through 29 July of 2009. All of the back trajectories show air parcels arriving into YVR from the north.

Figure 2.8: Smoke event from 27 July through 29 July 2009

Figure 3.7 shows the SFD imagery along with the single particle HYSPLIT back trajectory. SFD shows that the fires were located in the interior of British Columbia during the smoke event. In addition, the smoke plume displayed on 28 July 2009 displays the smoke to be heavier in certain regions than others. For example, the smoke plume was darker closer to the location of the fire and near Vancouver, and the smoke plume was lighter on Vancouver Island, displaying less smoke present. The HYSPLIT single backward trajectory in Figure 3.7 indicates the parcel descending to YVR on 29 July 2009. The backward trajectory models the trajectory of the parcel backward for 72 hours, demonstrating the air parcel was transported from the north into YVR. A single backward trajectory was computed at 500 m A.G.L as it is a clear representation of the movement of the air parcel. Therefore, from examining the SFD imagery and HYSPLIT trajectory it was determined that the smoke from forest fire was transported southward from fires located...
to the north into the Greater Vancouver region. Results from HYSPLIT proved to be consistent with the smoke plumes shown on the SFD.
Figure 2.9: Top: SFD imagery from 28 July 2009. Bottom: HYSPLIT trajectory on 28 July 2009 during July-August 2009 smoke event.
Figure 2.10 shows the fine (blue) and coarse (red) mode particle optical depths during the 27 July through 05 August 2009 smoke event. During this smoke event, the fine mode optical depths reach maxima of 0.74 nm at 3pm on 28 July 2009. Another increase of fine mode particle AOD was experienced on 03 August 2009 reaching a AOD of 0.52 nm. Peaks in fine mode optical depth took place during the smoke event identified on the SFD. Figure 2.10 displays the peak in fine mode AOD starting late on 27 July, after the peak the particles tend to vary in optical depth until they reach another maxima on 03 August 2009. Comparing the fine mode particle maximum of 0.745 nm in the July- August 2009 smoke event to a maximum of 0.41 nm during an August 2008 smoke event (Figure 2.3), the fine particle optical depths are almost doubled during the July-August 2009 smoke event.
Results from the lidar imagery suggest a heavy presence of smoke in the LFV which would significantly degrade air quality. Lidar (light detection and ranging) imagery which is a part of the CORAL-Net (Canadian Operational Research Aerosol lidar network) was analyzed for the duration of the case study. Backscatter ratios at 532 nm produced by the lidar located on the western edge of the University of British Columbia grounds are shown in Figure 2.11. UBC-CORALNet lidar data is described and discussed in full by McKendry et al. (2011a). The presence of forest fire smoke was evident in all of the lidar backscatter images at 532 nm,
as it is shown in blue on the imagery. On the lidar imagery clouds are shown in white. Smoke extended through the troposphere on each day of the smoke event, reaching an approximate height of 4 km A.G.L on 27 July through 30 July 2009. The structure of the smoke plume varied through the event but subsidence was evident later in the case study shown by the decrease in the height of the smoke layer (blue colour on the backscatter imagery).
Figure 2.11: Lidar images at 532 nm from UBC starting on 27 July through 06 August 2009, smoke layer is shown in blue while clouds are shown in white.
To further examine the impacts of forest fire smoke on air quality, PM$_{2.5}$ and O$_3$ concentrations were examined at YVR. Hourly concentrations of PM$_{2.5}$ and O$_3$ were analyzed from 24 July through 06 August 2009 (Figure 2.12). Concentrations of PM$_{2.5}$ began to increase from 9.9 $\mu$gm $^{-3}$ on 26 July and continued to increase to a maximum hourly concentration of 26.2 $\mu$gm $^{-3}$ pm 30 July. Increased concentrations of PM$_{2.5}$ took place on days in which the SFD showed the presence of smoke in the LFV. Hourly concentrations of O$_3$ clearly show expected diurnal patterns, in which concentrations increase during the daytime and decrease after sunset (Figure 2.12). During the smoke event, levels of O$_3$ were also seen to increase from 28 July through 04 August. High concentrations of O$_3$ which reached between 38-61 ppb at YVR were likely due to the presence of forest fire smoke and meteorological conditions. AOD also experienced peaks in fine mode optical depths at the same time that PM$_{2.5}$ experienced increase in concentrations, the patterns of the two variables are very similar.

![Hourly PM$_{2.5}$ Concentrations at YVR](Image)

![Hourly Ozone Concentrations at YVR](Image)

Figure 2.12: PM$_{2.5}$ (left) and O$_3$ (right) concentrations at YVR from 24 July through 05 August 2009.

KatKam images are shown in Figure 2.13 to illustrate the impact of forest fire smoke on local visibility over English Bay. The digital image on the left side of Figure 2.13 is taken on 30 July 2009 at 12pm during the smoke event examined in this case study. While the KatKam image on the right in Figure 2.13 is taken on 16
August 2009 at 12 pm which is not a smoke day. On the KatKam image from 30 July 2009 the buildup of particles in the atmosphere is apparent as the mountains are not visible in the background, whereas on 16 August 2009 the mountain range is clearly outlined. The colour of the atmosphere is distinctly different in the two images; 30 July shows a buildup of smoke particles while on 16 August the atmosphere appears cleaner. From this case study it can be concluded that smoke from forest fires did negatively impact air quality in the Georgia Basin airshed.

![KatKam imagery](image)

Figure 2.13: KatKam imagery during a smoke and non-smoke day. Left: 30 July 2009 during a smoke event. Right: 16 August 2009 on a non-smoke day. Source: Telemark Systems. (2012) by permission.

2.5 Conclusions

In this chapter, a combination of tools (SFD and HYSPLIT) and datasets (AERONET, fire statistics, CORALNet) were used to determine the frequency of summer days in which smoke was present over the Georgia Basin region. The number of smoke events in the Georgia Basin airshed varies from year to year. In total there were 77 smoke days. Frequencies of smoke events were significantly influenced by temperature and precipitation during the summer months. SFD imagery identified the summer of 2009 to have the most smoke days and the summer of 2011 with the least. In addition, smoke events can occur on up to 30% of summer days, as in 2009, which is a significant portion of the summer.

Forest fire smoke has been shown to travel over long-distances (up to 1000 km). It was shown that during smoke events there is significant cross border transport,
with up to 60% of smoke events in the Georgia Basin originating from the western States of the USA in 2008. PM$_{2.5}$ transport across the Canada-US international border varied from year to year. For instance, in 2008 the majority of smoke days were caused by fires in northern California, whereas in 2010 the smoke days were mainly caused by forest fires in northern British Columbia. Cross border transport up for 60% is large and could potentially lead to violations of Canada Wide Standards (CWS) for PM$_{2.5}$ and O$_3$. The majority of air parcels arriving into YVR originated in Canada or on the Pacific.

The case study from 27 July through 05 August of 2009 suggests the potential for forest fire smoke to significantly impact air quality and visibility in the LFV. The case study gives a better understanding of how the combination of SFD, AOD and HYSPLIT can be used together to identify smoke days and to track the transportation of smoke throughout the atmosphere. Investigating forest fire events such as the July to August event in 2009 is an example of a poor air quality event, which is likely to happen more frequently in the future, impacting air quality. Furthermore, using all of these tools allows for a thorough investigation of the smoke event. The use of these tools proved that they are reliable to use to determine smoke days and the transport of air parcels during forest fire smoke events. These methods could be used in other locations to help better predict the transport of pollutants and improve air quality forecasting. On this basis, the impacts and details of these events are explored in more detail in the next two chapters.
Chapter 3

Forest fire impacts on PM$_{2.5}$ and O$_3$ concentrations

3.1 Introduction
Forest fires are known to produce numerous pollutants such as carbon dioxide (CO$_2$), carbon monoxide (CO), oxides of nitrogen (NO$_x$), volatile and semi-volatile organic compounds (VOC and SVOC), particulate matter (PM), ammonia (NH$_3$), sulphur dioxide (SO$_2$), and methane (CH$_4$) (Wiedinmyer et al., 2006). The presence of O$_3$ precursors from biomass burning in combination with sunlight can lead to the production of O$_3$ (Jaffe et al., 2008a). Particulate matter can travel long distances and is known to have adverse health impacts. Certain synoptic weather patterns are conducive to high concentrations of photochemical pollutants which can significantly degrade air quality during the summer months. Given the projected increase in forest fire events with global climate change, and the increasingly stringent regulation of urban air pollution, it is important to determine the extent to which local PM and O$_3$ concentrations are enhanced during forest fire events. Episodic degradation of air quality from local anthropogenic sources combined with forest fire smoke may lead to violation of Canada Wide Standards for PM$_{2.5}$ and O$_3$. The methods used to determine the amount which PM$_{2.5}$ and O$_3$ concentrations were enhanced during smoke events are similar to those of Jaffe et al. (2008a). Jaffe et al. (2008a) concluded that forest fire smoke resulted in av-
verage annual enhancements of approximately 1 microgram per cubic meter at five different regions examined.

3.2 Background

3.2.1 Meteorology and pollutant concentrations

Meteorology is known to play a significant role on the transport and dispersion of pollutants. The Georgia Basin airshed is located in a region of complex coastal terrain. Air pollution meteorology in the LFV is very involved and is largely modulated by weather patterns that influence the airshed (Thomson and Yukon Region, 2004). Thermo-topographic circulations and mechanical channeling of the large scale flow by mountainous terrain are important aspects of the regions’ meteorology. Approximately 2.4 million people reside within the LFV. As the population of the LFV continues to increase, regulating air quality is becoming more important. Within the LFV a large portion of the population is located in the vicinity of metropolitan Vancouver in the northwestern corner of the LFV. Three major influences on dispersion of pollutants within the atmosphere are wind speed, wind direction and atmospheric stability. Wind speed and direction are important as they determine where pollutants are transported from especially since small particles can be transported over long distances. Also the strength and location of meteorological systems play a large role on the transportation, deposition and dispersion of pollutants (McKendry, 2000).

Synoptic scale weather patterns largely influence the concentrations of PM$_{2.5}$ diurnally and seasonally. During the winter and spring months in the LFV pollutants tend to follow a diurnal pattern. It has been observed that concentrations increased during the morning and after sunset. In the spring months there is frequently an inversion after sunset around 6pm due to the cooling of the surface. In the winter months elevated levels of PM$_{2.5}$ are associated with occasional Arctic outflow events, in which a high pressure system brings strong winds to southwestern British Columbia. McKendry (2000) explains that during the summer months the LFV experiences daytime sea breezes which increase the frequency of westerly, up-valley flow. Furthermore, the westerly up-valley flow is known to transport ur-
ban pollutants across the LFV (McKendry, 2000). During the summer months, the region is known to experience high concentrations of O$_3$ and PM during upper level high pressure events. Anticyclones which persist for days decrease the transport and dispersion of pollutants (McKendry, 2000). Anticyclonic events which cause a buildup of pollutants in the lower atmosphere tend to happen in the months of July and August when it is hot and dry. In addition, in the summer a thermal trough is created which is driven by heating of land which leads to conditions conducive to elevated levels of PM$_{2.5}$.

### 3.2.2 Sources and sinks of PM$_{2.5}$ and O$_3$ in the Georgia Basin airshed

Pollutants can be emitted from primary and secondary sources. A primary pollutant is directly emitted from the source, whereas secondary pollutants arise from transformational processes within the atmosphere. Secondary pollutants may be produced by processes that are chemical, photochemical or aqueous. For example, O$_3$ is a secondary pollutant, formed through a chemical reaction between NO$_x$, VOC and sunlight (Yarnal, 1993). Given the small, fine size of PM$_{2.5}$ which behaves much like a gas, it is easily transported over further distances than other pollutants and takes longer to be removed or settle. Therefore, PM$_{2.5}$ will stay in the atmosphere much longer and tends to be removed by precipitation. The Georgia Basin airshed has numerous sources and sinks of PM$_{2.5}$ and O$_3$. Some of the air pollution observed in the Georgia Basin airshed is local (spatial scale of order 5 km) but air pollution has also been traced on a regional scale (50-500 km) and global scale (Thomson and Yukon Region, 2004).

MoE. (2007), states that some sources of PM include dust, soot, and smoke from vehicles, marine vessels, power plants, factories, construction, residential wood burning and forest fires. As Vancouver is a port, there are continuously ships entering and leaving the Georgia Basin airshed, emitting pollutants. In addition, there are numerous highways throughout the LFV which are used by commuters and trucks to transport materials. Certain monitors have higher background concentrations of PM$_{2.5}$ and O$_3$ due to the close proximity to the highway and vehicle emissions. For example, the monitor located in Kitsilano (T002) is within the city, and experiences higher concentrations of vehicle emissions compared to a monitor.
located further away from roadways. The eastern portion of the LFV is dominantly agricultural and flat, therefore being a source of dust and soot. The northern part of the LFV has mountains rising over 1km above the valley floor.

### 3.2.3 Synoptic typing classification

Synoptic typing is commonly used to classify each day based on the dominating weather pattern. Yarnal (1993) defines synoptic climatology as "the relationship between the atmosphere and the surface environment", taking into account atmospheric circulation and all factors influencing the surface. In order to ensure that days affected by smoke in the Georgia Basin were compared with a sample of days with like meteorological conditions, all smoke and non-smoke days were classified into synoptic types. Otherwise the difference in PM$_{2.5}$ and O$_3$ concentrations during smoke and non-smoke events could be due to differing weather patterns and not the presence of forest fire smoke.

The weather type classification used for the purpose of this research is similar to classification methods used by Reuten et al. (2012) and described by Yarnal (1993). When using a weather type classification, it is important that upper level conditions and surface observations are taken into account (Yarnal, 1993). Weather type classification was created using a Principal Component Analysis (PCA) combining the sea level pressure (SLP) and 500 hPa geopotential heights (GPH) for the months of April through September from 1948-2012 using NCEP Re-analysis product. PCA is a very common type of analysis within the meteorology/climatology field. For the purpose of this research the years of 2008-2011 were extracted from the catalog. A PCA was conducted on the NCEP Re-analysis product combined SLP and GPH fields. PCA (Reuten et al., 2012) explains that both fields had equal weighting and were standardized by subtracting their mean and dividing by their standard deviation of all daily values, eventually stacking the SLP and GPH in a single vector. The PCA uses orthogonal transformation to convert all of the data into linearly uncorrelated principal components. Furthermore, the empirical orthogonal functions (EOFs) of an orthogonal coordinate system are determined to minimize the difference between all vectors and the EOFs (Reuten et al., 2012). Vectors for SLP and GPH are created based on the PCA. K-means clustering was
used to group the vectors for each day of the study period. K-means is a type of clustering which groups variables into clusters; each variable is put into a K cluster with the most similar mean value. This research used 12 EOFs therefore clustering was done in 12-dimensional space. The vectors created in 12-dimensional space were then grouped using k-means clustering using Euclidean distance, and random initial seeding (Reuten et al., 2012). SLP and GPH were associated with a similar cluster or weather typing. Eight clusters of different weather patterns (Figure 3.1) were produced. The weather typing catalog has been updated for the purpose of this study by Derek van der Kamp (pers comm). The weather typing was used to determine which weather types typically lead to smoke days and non-smoke days. It was also determined if smoke days were common which each weather type.

Figure 3.1: Synoptic weather type classification map with eight different common weather patterns in the LFV.
3.3 Methods

This section describes the methods used to determine the non-smoke days and how the non-smoke days were compared to smoke days.

3.3.1 Data

To determine the extent to which PM$_{2.5}$ and O$_3$ concentrations were enhanced during forest fire smoke events, hourly data from twelve different stations across the Georgia Basin region (stations are listed in Table 3.1) were analyzed. The monitors chosen had to meet specific criteria. Firstly, they had to show a geographic spread to capture the distribution across the Georgia Basin airshed, as shown in Figure 3.2. Secondly, the monitors had to have a significantly long and reliable record of hourly PM$_{2.5}$ and O$_3$ concentrations. The observation monitoring network run by the British Columbia Ministry of the Environment is a very rare and dense observational network. Given that the observational network is so dense, it is difficult to replicate this analysis in other parts of the world. Port Moody was missing 40 records of PM$_{2.5}$ concentrations and North Vancouver was missing 24 records of PM$_{2.5}$. All of the monitors had complete records of O$_3$ concentrations. Ten of the twelve stations chosen are spread out across the LFV with one station located in Nanaimo and one in Whistler.
Figure 3.2: PM$_{2.5}$ and O$_3$ monitor locations across the LFV, excluding Nanaimo and Whistler.
Table 3.1: PM$_{2.5}$ and O$_3$ monitor locations analyzed across the Georgia Basin airshed.

<table>
<thead>
<tr>
<th>Number</th>
<th>Station ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>T002</td>
<td>Kitsilano Secondary</td>
</tr>
<tr>
<td>T004</td>
<td>Burnaby Kensington</td>
</tr>
<tr>
<td>T006</td>
<td>North Vancouver Second Narrows</td>
</tr>
<tr>
<td>T009</td>
<td>Port Moody</td>
</tr>
<tr>
<td>T012</td>
<td>Chilliwack</td>
</tr>
<tr>
<td>T018</td>
<td>Burnaby South</td>
</tr>
<tr>
<td>T020</td>
<td>Pitt Meadows</td>
</tr>
<tr>
<td>T027</td>
<td>Langley</td>
</tr>
<tr>
<td>T029</td>
<td>Hope Airport</td>
</tr>
<tr>
<td>T031</td>
<td>YVR</td>
</tr>
<tr>
<td>W</td>
<td>Whistler</td>
</tr>
<tr>
<td>N</td>
<td>Nanaimo</td>
</tr>
</tbody>
</table>

For the purpose of this research, average daily concentrations of PM$_{2.5}$ were calculated from hourly concentrations. Instead of examining the average daily concentration of O$_3$, the maximum daily concentration from 0-24 hour was determined at each station. Maximum daily O$_3$ concentrations were analyzed as peak concentrations are considered a better metric of the influence of O$_3$ on human health. Data were analyzed to determine the diurnal and annual patterns and to identify changes during smoke events. Interannual trends were investigated to determine which years experienced more smoke days and how much the smoke was enhanced.

Once the average daily PM$_{2.5}$ and maximum daily O$_3$ concentrations were computed, the synoptic weather typing was determined for each of the smoke and non-smoke days. Using the weather typing catalog also helped to determine the type of weather that was influencing the region. The weather typing was used to classify the smoke days and also acted as a control variable instead of randomly choosing non-smoke days. First, it was determined which weather types took place on each of the smoke days. After counting the number of smoke days within each
weather type, the frequency distribution of all the smoke days was calculated. A sample of non-smoke days was then randomly generated so that the frequency distribution for smoke and non-smoke days was the same for each weather type. This ensured that weather variability was not a factor influencing statistical differences between the smoke and non-smoke sample sets. The size of this sample was maximised to ensure a full range of within-type variability within the sample. The sample of non-smoke days has a greater number of variables than the smoke sample but both samples include the same percent of each weather type.

For the four-year period from 2008-2011, a total of 77 smoke days were analyzed and compared to 153 non-smoke days. Comparing smoke and non-smoke days with similar weather patterns decreases the possibility that the difference in PM$_{2.5}$ and O$_3$ concentrations during are due to differing weather types. Mean daily PM$_{2.5}$ and maximum O$_3$ concentrations were calculated, along with the minimum and maximum concentrations. The mean daily PM$_{2.5}$ concentrations for smoke days were compared to the mean daily PM$_{2.5}$ for non-smoke days. O$_3$ concentrations were compared during smoke and non-smoke events to determine the enhancements during smoke events. In addition to comparing the mean concentrations of pollutants, a paired t-test was computed so that the mean concentrations would be compared by station. A similar approach was adopted by Jaffe et al. (2008a), in their analysis of variations of PM$_{2.5}$ during smoke events in the western United States. Jaffe et al. (2008a) examined five different regions across the western United States.

3.4 Results and discussion

3.4.1 Identification of smoke and non-smoke days

Smoke day frequencies throughout the study period show considerable interannual variability. In southwestern British Columbia, the fire season of 2009 experienced the most smoke days with the months of July and August having the most smoke days on record, due to high temperatures and low precipitation. Daily weather types for LFV were extracted for the period 2008-2012. To determine the dominant weather patterns during the summer months, a frequency distribution was created.
for all the non-smoke days for the four year study period and compared the frequency on smoke days (Figure 3.4). The frequency distribution used to compare the smoke and non-smoke days is shown in Figure 4.1. Two of the most common summer weather types that lead to smoke events are type 5 (Figure 3.5) and type 7 (Figure 3.6).

**Figure 3.3:** Frequency distribution of synoptic typing on smoke (red) and non-smoke (blue) days. The frequency distributions for smoke and non-smoke days are as similar as possible. The non-smoke subset contains double the amount of days as the smoke subset.
Weather type 5 was the most common weather type during smoke events and is characterised by a ridge of high pressure centered over the Central Pacific at 500 hPa (red) and a weak trough over the Pacific Coast at 500hPa (Figure3.5). Surface pressure (blue) show northeasterly winds, shown with a blue arrow (Figure3.5). This weather pattern is consistent with bringing smoke from the interior and northern British Columbia to the Georgia Basin airshed. Furthermore, this weather pattern is not likely to create conditions favourable to produce forest fires but the typing is good for transport from the interior to the LFV.

Figure 3.4: Frequency distribution of synoptic typing on all non-smoke days for all summers compared to synoptic classification on smoke days.
Figure 3.5: Weather type 5, one of the most common weather types from 2008-2011 in the LFV.

Type 7 was the second most common weather pattern type during smoke events and is characterised by a ridge of high pressure over the west coast (Figure 3.6). This pattern is conducive to subsidence, clear skies and elevated temperatures. During the summer months this weather type produces poor air quality in the LFV. The sea level pressure (blue) shows a very ”slack” pressure gradient across British Columbia, causing light wings and a ridge of high pressure. This weather pattern is likely to produce forest fires as it is sunny and warm. Additionally, this pattern is likely to promote northward transport from the south along the coast.
3.4.2 Particulate matter

All twelve of the monitors across the Georgia Basin airshed experienced increased levels of PM$_{2.5}$ during forest fire events (Figures 3.7 and 3.8). Mean daily concentrations of PM$_{2.5}$ increased on average by 4.45 $\mu$gm $^{-3}$ at all monitors during smoke events. During smoke events, average daily concentrations of PM$_{2.5}$ were 9.77 $\mu$gm $^{-3}$ across all monitors, with increases as high as 176% observed at some locations. On average at all monitors examined, PM$_{2.5}$ concentrations are enhanced by 48% during smoke events. Specifically, average daily concentrations of PM$_{2.5}$ were highest in Whistler and at monitors located further from the coast. Concentrations are higher away from the coast as these monitors are located in closer proximity to fires and due to air flow patterns. The smallest enhancement of PM$_{2.5}$ was YVR with an enhancement of 3.5 $\mu$gm $^{-3}$. The minimum and maximum mean daily concentrations of PM$_{2.5}$ are shown in Table 3.2. A paired t-test showed there was a significant difference between the mean smoke and non-smoke
concentrations of PM$_{2.5}$. 

The monitor located in Kitsilano experienced an increase of 87% in average daily concentrations of PM$_{2.5}$ during smoke events shown in the top graph of Figure 3.7. Kitsilano is located on the western side of the Georgia Basin, in an urban area, close to roadways and English Bay.

Enhancements of PM$_{2.5}$ in Kitsilano, North Vancouver, Burnaby Kensington and YVR are shown in the top graph in Figure 3.7. During smoke events, concentrations of PM$_{2.5}$ increased by 62% in North Vancouver. The monitor is North Vancouver is located in an urban area near the Vancouver Harbour which experiences a lot of ship activity daily. Burnaby Kensington saw an average daily increase of 78% of PM$_{2.5}$ during smoke events. YVR saw an average daily increase of 72% during smoke events. Although YVR experienced a substantial increase in concentrations of PM$_{2.5}$, the enhancement was one of the smallest when compared to other monitors.

The bottom graph in Figure 3.7 shows the average daily concentrations of PM$_{2.5}$ at monitors located in Port Moody, Chilliwack, Burnaby South and Pitt Meadows. Port Moody, which is located at the edge of the Burrard Inlet, experienced an average daily increase of 80% which was the smallest increase out of all 12 monitors analyzed. The monitor in Port Moody was missing 27 days of data, 13 days of missing data were classified as smoke days and the monitor was missing 14 days of non-smoke data. Due to the missing data, the enhancement of 68% may not be fully represent how much PM$_{2.5}$ was increased during smoke events in Port Moody. Chilliwack is located in the flat, agricultural portion of the LFV. During smoke events, concentrations of PM$_{2.5}$ were enhanced by 84% in Chilliwack. Further, Chilliwack had a maximum outlier of 27 $\mu$gm$^{-3}$ during smoke events, which is just below the daily CWS of 30 $\mu$gm$^{-3}$. The monitor in Chilliwack also has other sources contributing to the high concentrations of PM$_{2.5}$ including agricultural practices and road traffic.

Burnaby South is located 12 km southeast of downtown Vancouver. Burnaby South is found in an urban/residential/industrial area. Burnaby South experienced a 67.8% increase in average daily concentrations of PM$_{2.5}$ during smoke events. Mean daily concentrations of PM$_{2.5}$ during smoke events was 8.85 $\mu$gm$^{-3}$ and 5.27 $\mu$gm$^{-3}$ during non-smoke events. Pitt Meadows is located in the eastern
portion of the LFV on the north side of the Fraser River. In addition, during smoke
events average daily concentrations of PM$_{2.5}$ were enhanced by 82%, which is one
of the largest enhancements within the LFV.
Figure 3.7: Comparison PM$_{2.5}$ during smoke and non-smoke events at eight monitor locations across the LFV.
Figure 3.8 shows the average daily concentrations of PM$_{2.5}$ during smoke and non-smoke events at monitors located in Langley, Hope, Nanaimo and Whistler. Langley is a semirural city located in the southeast corner of the LFV and north of the Canada-US border. During smoke events Langley experienced a 79% increase in PM$_{2.5}$ during smoke events. Hope is situated in the far eastern portion of the LFV in a rural area, in close proximity to the Trans-Canada highway. The third largest enhancement of PM$_{2.5}$ during smoke events was in Hope, with an enhancement of 89%. Nanaimo and Whistler experienced the largest enhancements in concentrations of PM$_{2.5}$ during smoke events. Nanaimo is a suburban city located on the southeast corner of Vancouver Island. Nanaimo is a very busy ferry terminal hub which experiences high ferry traffic daily. Average daily concentrations of PM$_{2.5}$ enhanced by 123% during smoke events in Nanaimo. A maximum average daily concentration of 48 $\mu$gm$^{-3}$ was experienced during smoke events. The monitor located in Whistler experienced the largest enhancements of PM$_{2.5}$ during forest fire smoke events. Average daily concentrations of PM$_{2.5}$ enhanced by 176% during smoke events in Whistler. In addition, a maximum average daily concentration of 59 $\mu$gm$^{-3}$ was experienced during smoke events, which is significantly higher than CWS for PM$_{2.5}$. The large enhancements of concentrations of PM$_{2.5}$ during smoke events at Whistler, is due to the fact that Whistler is in close proximity to the locations of the of the fire in many cases, as shown in the SFD imagery in the previous chapter. Also the monitor located in Whistler is located within a valley, making the area susceptible to high concentrations of pollutants as the valley channels smoke and the meteorology of the valley leads to poor ventilation.
Figure 3.8: Comparison of PM$_{2.5}$ concentrations during smoke and non-smoke events.
Table 3.2: Particulate matter statistics. Smoke events on top and non-smoke events on the bottom.

<table>
<thead>
<tr>
<th>PM</th>
<th>T002</th>
<th>T004</th>
<th>T006</th>
<th>T009</th>
<th>T012</th>
<th>T018</th>
<th>T020</th>
<th>T027</th>
<th>T029</th>
<th>T031</th>
<th>W</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>9.08</td>
<td>10.16</td>
<td>11.36</td>
<td>11.86</td>
<td>9.57</td>
<td>8.851</td>
<td>10.34</td>
<td>9.24</td>
<td>9.56</td>
<td>8.402</td>
<td>11.18</td>
<td>7.64</td>
</tr>
<tr>
<td>Median</td>
<td>7.425</td>
<td>9.28</td>
<td>10.87</td>
<td>10.52</td>
<td>8.81</td>
<td>7.84</td>
<td>9.983</td>
<td>8.49</td>
<td>8.17</td>
<td>7.16</td>
<td>9.43</td>
<td>5.71</td>
</tr>
<tr>
<td>Min</td>
<td>2.62</td>
<td>2.84</td>
<td>2.85</td>
<td>2.98</td>
<td>2.1</td>
<td>2.6</td>
<td>3.31</td>
<td>2.58</td>
<td>1.38</td>
<td>2.57</td>
<td>1.29</td>
<td>0.81</td>
</tr>
<tr>
<td>Max</td>
<td>32.32</td>
<td>35.28</td>
<td>23.13</td>
<td>37.46</td>
<td>27.4</td>
<td>28.47</td>
<td>36.33</td>
<td>28.84</td>
<td>33.14</td>
<td>27.12</td>
<td>59.47</td>
<td>48.33</td>
</tr>
<tr>
<td>SD</td>
<td>5.409</td>
<td>5.428</td>
<td>4.44</td>
<td>5.83</td>
<td>4.68</td>
<td>4.607</td>
<td>5.41</td>
<td>4.766</td>
<td>6.09</td>
<td>5.114</td>
<td>10.55</td>
<td>8.254</td>
</tr>
<tr>
<td>NA's</td>
<td>1</td>
<td>0</td>
<td>16</td>
<td>13</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>0</td>
</tr>
</tbody>
</table>

| Mean | 5.3 | 5.705| 7.027| 7.054| 5.202| 5.274| 5.668| 5.167| 5.061| 4.902| 4.045| 3.417|
| Median| 4.76| 5.52 | 6.43 | 5.83 | 4.9  | 4.69 | 5.23 | 4.695| 4.545| 4.65 | 3.32 | 2.99 |
| Min  | 0.92| 1.28 | 2.08 | 1.29 | 0.6  | 0.68 | 1    | 0.72 | 0.53 | 0.91 | 0.24 | 0.29 |
| Max  | 12.56| 15.3 | 19.13| 23.18| 17.92| 13.51| 14.05| 12.44| 22.25| 15.02| 17.7 | 12.21|
| SD   | 2.356| 2.85115| 2.95383| 3.9677| 3.059| 2.49 | 2.76 | 2.65 | 3.25 | 2.23 | 2.97 | 2.149|
| 1st  | 3.71 | 3.61 | 4.892| 4.54 | 2.975| 3.47 | 3.81 | 3.18 | 2.548| 3.35 | 2.36 | 1.89 |
| NA's | 4    | 0    | 25   | 14   | 0    | 0    | 4    | 3    | 1    | 0    | 0    | 0   |
3.4.3 Ozone

Concentrations of $O_3$ significantly increased at all monitors across the Georgia Basin airshed during smoke events. On average, maximum daily concentrations of $O_3$ increased by 7.95 ppb during forest fire smoke events. The largest enhancements in $O_3$ concentrations were observed at monitors located further away from the coast (Hope, Chilliwack and North Vancouver). The largest enhancements in $O_3$ are located at different monitors than those with the largest enhancement of PM$_{2.5}$. The monitors with the most significant enhancements in $O_3$ are located in the eastern portion of the LFV, which is known to experience high concentrations of $O_3$.

Figure 3.9 shows concentrations of $O_3$ during smoke events at monitors located in Kitsilano, North Vancouver, Burnaby Kensington and YVR. Kitsilano experienced a 20% increase in maximum daily concentrations of $O_3$ during smoke events. Average daily maximum concentrations of $O_3$ in North Vancouver increased by 42% during smoke events. The mean of the daily maximum concentrations of $O_3$ were lowest in North Vancouver during both smoke and non-smoke events. The smallest enhancement of average daily maximum $O_3$ concentrations was observed at the monitor located in Burnaby Kensington, with an increase of 26% during smoke events. Kitsilano, North Vancouver and Burnaby Kensington experienced some of the lowest concentrations of maximum daily $O_3$ out of all twelve monitors.

The graph on the bottom of Figure 3.9 displays maximum daily concentrations of monitors located in Port Moody, Chilliwack, Burnaby South and Pitt Meadows. Each of the four monitors shown in the bottom of Figure 3.9 experienced higher concentrations of $O_3$ during smoke events when compared to other monitors. Port Moody experienced a 23% increase in average daily maximum concentrations of $O_3$ during smoke events. Chilliwack which is located in the eastern portion of the LFV in an agricultural setting saw the largest increase in mean daily maximum concentrations of $O_3$ during smoke events. Mean daily maximums increased by 34% in Chilliwack. Pitt Meadows which is also located on the eastern portion of the LFV experienced the largest maximum daily concentration of $O_3$ during smoke events reaching 97 ppb. The mean daily maximum concentrations of $O_3$ increased by 26% during smoke events.
Figure 3.9: Comparison ozone during smoke and non-smoke events at eight monitor locations across the LFV.
Maximum daily concentrations of O$_3$ at monitors located in Langley, Hope, Nanaimo and Whistler are shown in Figure 3.10. Langley, which is located east of Vancouver in a sub-urban/industrial setting experienced a 25% increase in mean daily maximum concentrations of O$_3$ during smoke events. Hope which is located 155 km east of Vancouver experienced the largest increase in mean daily maximum concentrations of O$_3$ with an increase of 35%. In addition, a maximum daily concentration of 95 ppb was observed during smoke events in Hope. During the summer months, the monitors in Langley and Hope experienced high concentrations of O$_3$ due to their distance from the source of O$_3$ precursors and due to topographic controls (narrow valley). Mean daily maximum concentrations of O$_3$ increased by 23% in Nanaimo. Whistler experienced one of the smallest increases in mean daily maximum O$_3$ with an increase of 20%. Monitors located further away from the city of Vancouver experienced higher concentrations of O$_3$, as there is naturally higher urban concentrations of O$_3$. For example, monitors located in North Vancouver, Hope and Chilliwack experienced the largest increases in O$_3$. 
Figure 3.10: Comparison of ozone during smoke and non-smoke events
Table 3.3: Ozone station data. Smoke events on top and non-smoke events on the bottom.

<table>
<thead>
<tr>
<th>PM</th>
<th>T002</th>
<th>T004</th>
<th>T006</th>
<th>T009</th>
<th>T012</th>
<th>T018</th>
<th>T020</th>
<th>T027</th>
<th>T029</th>
<th>T031</th>
<th>W</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>36.87</td>
<td>36.54</td>
<td>32</td>
<td>37.14</td>
<td>48.88</td>
<td>35.49</td>
<td>42.25</td>
<td>45.13</td>
<td>50.84</td>
<td>35.45</td>
<td>42.2</td>
<td>36.43</td>
</tr>
<tr>
<td>Median</td>
<td>37</td>
<td>35</td>
<td>32</td>
<td>37</td>
<td>46</td>
<td>36</td>
<td>42.4</td>
<td>46</td>
<td>48</td>
<td>35.6</td>
<td>42.3</td>
<td>34.3</td>
</tr>
<tr>
<td>Min</td>
<td>0</td>
<td>17</td>
<td>7</td>
<td>6.4</td>
<td>17.6</td>
<td>0</td>
<td>0.9</td>
<td>17.3</td>
<td>19.8</td>
<td>17.3</td>
<td>17.1</td>
<td>19.3</td>
</tr>
<tr>
<td>Max</td>
<td>68</td>
<td>78</td>
<td>61.2</td>
<td>93</td>
<td>90</td>
<td>79</td>
<td>97.4</td>
<td>94</td>
<td>95</td>
<td>62</td>
<td>62</td>
<td>68.4</td>
</tr>
<tr>
<td>1st</td>
<td>29</td>
<td>29.25</td>
<td>24</td>
<td>25.5</td>
<td>34.5</td>
<td>29</td>
<td>32.9</td>
<td>35.85</td>
<td>35.4</td>
<td>28.75</td>
<td>35.4</td>
<td>27.55</td>
</tr>
<tr>
<td>3rd</td>
<td>43</td>
<td>42.5</td>
<td>39.7</td>
<td>49.6</td>
<td>61.95</td>
<td>42.5</td>
<td>52.5</td>
<td>54</td>
<td>64.5</td>
<td>41.5</td>
<td>48</td>
<td>43.5</td>
</tr>
<tr>
<td>NA's</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

| Mean | 30.39| 28.96| 26.05| 30.12| 36.36| 29.35| 33.43| 36.19| 37.66| 30.53| 34.97| 29.71|
| Median| 30  | 28   | 26.2 | 31   | 35   | 30   | 32.5 | 36   | 36   | 30   | 34.1| 29  |
| Min  | 0    | 11.3 | 0    | 4.1  | 14.5 | 0    | 0    | 18.2 | 14   | 10   | 15  | 15.8|
| Max  | 68   | 69   | 63   | 75   | 79   | 69   | 70   | 70   | 82.7 | 74   | 66  | 61  |
| 1st  | 26   | 20   | 20   | 22   | 27.85| 25.35| 26.2 | 30   | 28.15| 25   | 29.3| 24.8|
| 3rd  | 36   | 34   | 32.5 | 36.95| 44.65| 34.5 | 39.45| 41.5 | 47   | 36   | 39  | 33.1|
| NA's | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0  | 0  |
Figure 3.11 provides a qualitative indication of the extent to which forest fire enhancements of PM$_{2.5}$ and O$_3$ may affect violation of the Canada Wide Standards in the Georgia Basin airshed. Average daily concentrations of PM$_{2.5}$ increase by 4.45 $\mu$gm$^{-3}$ during smoke events and O$_3$ increases by 7.95 ppb during smoke events, which is shown in relation to CWS and background concentrations. Figure 3.11 indicates that if the magnitude and frequency of forest fires increases, and if background concentrations increase, it is likely that forest fires smoke enhancements are of sufficient magnitude to result in violation of air quality standards in the Georgia Basin in both the present and increasingly in the future.

Figure 3.11: O$_3$ and PM$_{2.5}$ impacts on air quality in relation to CWS. The CWS are drawn in red.

3.5 Conclusions

During the four year study period from 2008-2011, summer-long enhancements of PM$_{2.5}$ and O$_3$ were seen at all monitor locations during smoke events. Mean daily PM$_{2.5}$ concentrations were doubled during smoke events. Specifically, Whistler experienced the largest enhancements in PM$_{2.5}$, which is likely since it is situated within a valley. Significant enhancements of O$_3$ were seen at all locations during smoke events. Average maximum daily concentrations of O$_3$ increased up to 26% which is an average increase of 7.95 ppb during smoke events. Each of the monitors across the LFV have different background levels of pollutants, influencing PM$_{2.5}$ and O$_3$ concentrations. Methods used to investigate PM$_{2.5}$ and O$_3$ concentrations can be applied to other areas in which air quality is influenced by forest
The results from this study can be used to improve air quality forecasts and informing the public about the significant increases in pollutants during smoke events.

Two weather patterns dominate the Georgia Basin airshed during the summer months. A ridge of high pressure is located over the Central Pacific in the first dominating weather pattern. Northeasterly winds associated with this weather pattern are likely to transport smoke from the interior in the Georgia Basin airshed. A ridge of high pressure is located over the west coast, bringing clear skies, warm temperatures and subsidence to the region. This weather pattern produces conditions favourable to produce forest fires. As these weather patterns are expected to become more frequent it is important to understand the role these patterns play on the transport and dispersion of smoke through the atmosphere. Further, synoptic weather typing is important as it can be done in other regions in which air quality is influenced by forest fire smoke to better understand the transport of smoke and the role weather patterns play on pollutant concentrations.

The enhancements of PM$_{2.5}$ during forest fire smoke events are in agreement with the findings of (Jaffe et al., 2008a). Jaffe et al. (2008a) saw a significant increase in PM$_{2.5}$ concentrations at numerous locations across the western United States, with average summer-long enhancements of PM$_{2.5}$ ranging from 0.61-1.84 $\mu$gm$^{-3}$, with values being double during large fire seasons. The PM$_{2.5}$ concentrations had a direct relationship with the area burned in the study done by Jaffe et al. (2008a).

The large enhancements of PM$_{2.5}$ and O$_3$ have proven to degrade air quality during forest fire smoke events. The increased levels of PM$_{2.5}$ and O$_3$ due to forest fire smoke in combination with the normal sources of pollution across the LFV produce very poor air quality during the summer months. As the frequency of forest fires are increasing, special attention needs to be given to forest fire smoke events. High concentrations of PM$_{2.5}$ and O$_3$ have been linked to negative health impacts. With a better understanding of the increase in PM$_{2.5}$ and O$_3$ concentrations better air quality forecasts can be made in the future. Furthermore, as the frequency of forest fires continues to increase understanding, the pollutant concentration increases is important for meeting Canada Wide Standards. Large increases in PM$_{2.5}$ and ozone can also significantly decrease atmospheric visibility. The role PM$_{2.5}$
plays on atmospheric visibility will be further investigated in the next chapter.
Chapter 4

Atmospheric visibility using digital images

4.1 Introduction

In this chapter, a method for calculating visual range based on digital “webcam” images is used to assess the impact of forest fire smoke on visibility in 2009 only. This method is an extension of that proposed by Janeiro et al. (2003) and is based on an approach under development at Environment Canada (Andrew Teakles, pers comm.). As such the results described herein represent a preliminary and exploratory assessment of an evolving technique. For future use, methods need to be re-defined based on the camera location and available nephelometer data.

In this study, this novel technique is assessed based on application to “KatKam” (www.katkam.ca) imagery located near the Burrard Street bridge and looking westward across English Bay. Nephelometer data from the eastern portion Lower Fraser Valley is used as a basis for validation.
4.2 Background

4.2.1 Atmospheric visibility

Atmospheric visibility has an impact on quality of life, happiness and tourism (Luo et al., 2002). According to Janeiro et al. (2007) reduced visibility is a result of high particle concentrations which absorb and scatter light. Pryor et al. (1995) notes that the during the summer months the LFV experiences impaired visibility and reduced air quality. Furthermore, particles produced by forest fires can influence visibility locally and regionally (Patterson and McMahon, 1984). Molenar et al. (2004) has shown that atmospheric visibility can be calculated using pixel data from images produced by digital cameras. Calculating atmospheric visibility using digital images is a reliable method that can replace more costly instruments such as nephelometers. To ensure the digital images are all extracting intensity values at the same location on each image, image metric techniques must be used (Janeiro et al., 2007), (Molenar et al., 2004). Since digital cameras can be moved in the vertical and horizontal direction due to rain or wind, the images must be registered. Calculating visibility from digital images is achieved by taking intensity values from specific targets within a scene. All of the images must be registered and aligned to relative to a reference image (Janeiro et al., 2007). In some cases depending on the movement of the camera images need to be translated, rotated and scaled (Janeiro et al., 2007). Once the images are registered and aligned, atmospheric extinction can be calculated using pixel intensity values. Targets must be selected in the background of the scene to calculate visibility. For the best results, it is recommended to use black targets in the background (Janeiro et al., 2003; Luo et al., 2002). Lastly, values for visibility calculated from digital images can be used to compared observed extinction values (Janeiro et al., 2003).

4.2.2 KatKam images

Digital images used for this research were obtained from KatKam (www.katkam.ca), a website created as a hobby that has been running for 16 years (see example KatKam image in Figure 4.1). The uploaded images are taken from the Telemark Systems Incorporated (TSI) building in Vancouver looking onto English Bay
(907 Beach Ave, Vancouver, British Columbia). The camera faces west-south-west looking onto English Bay the majority of the time. On occasion the owner of the camera does move the camera in the vertical and horizontal direction. In most cases the University of British Columbia can be seen on the left side, and the Coastal Mountain range on the right. More specifically, Bowen Island and sometimes West Vancouver can be seen on the right side of the digital images. The images are taken every five minutes with a 2004 Olympus C-5060 Widezoom digital camera. The camera was down for short periods and during periods of heavy rain the camera had rain drops on the lens. The owner of the camera states on their website that there are no filters used on the camera and that the camera compensates for clouds at dawn and dusk.

![KatKam image taken 03 June 2009 at 12 pm. Source: Telemark Systems. (2012) by permission.](image)

**Figure 4.1:** KatKam image taken 03 June 2009 at 12 pm. Source: Telemark Systems. (2012) by permission.
4.3 Methods

Before calculating visibility using digital images many steps were taken to prepare the images for analysis. First, all images were manually downloaded from www.katkam.ca by permission. The images were downloaded for 2009 the months of April through October at 9 am, 12 pm and 3 pm of each day. After all of the images were downloaded, black targets in the background so that later on they could be used to calculate extinction. The targets were chosen based on the distance to the camera. Since the camera is controlled by the owner, there was no control over where the camera was looking, the zoom or the focus. Therefore images which zoomed in large amounts were also deleted, along with images that moved away from the scene. Final images included all targets in the scene.

To calculate atmospheric visibility the first step was to register and align all of the digital images so that they were focused on the same scene. The purpose of registering and aligning all of the images was so the target intensity would be taken from each target at the exact same pixel location on every image. The images were registered in ImageJ. ImageJ is an open source image processing tool and can analyze large sets of images using marcos (automation of tasks) or plugins. Then a reference day was picked out of the set of images. The reference day was considered to be a "perfect" day out of the set of images. For the purpose of this research "perfect" was defined as the day with the best visibility, or the day in which the atmosphere was clearest. 03 June 2009 at 12pm was chosen as the reference day.

The registration of the images can be done manually, or semi-automatically. TurboReg automatically aligns all of the images to the target image (reference day). The first step of registration was to determine landmarks in the scene which were then used to match the images. Once the landmarks were determined, TurboReg ran through all of the images and registered and aligned each image to the reference image. The registered image has black in the area which the image has been corrected to match the reference image. MtrackJ is a plug-in that is used to manually track the movement of objects within an image.

The image registration turned out to be difficult process. The camera is never perfectly still, as there are errors associated with the mounting and adjusting of the
camera along with vibrations and movement because of wind. Once the plug-ins were tested on a smaller set of images then registered the entire set of images. After attempting to register the images numerous times large shift in the camera and the images would not align. Images from the fire season (April-October) for 2009 were registered. A reference day was chosen (03 July 2009). Once the TurboReg was done then MtrackJ was used to register any images that still needed to be corrected after the TurboReg. Using the MtrackJ plug-in completed the registration process.

Once the registration process was complete, a viewshed analysis was completed using ArcGIS. The viewshed was done to determine the exact distance each target was from the camera. The targets in the background were selected prior to the viewshed analysis. The first step to identify the pre-selected targets was to use a 30 metre resolution Digital Elevation Model (DEM) of southwestern British Columbia for the viewshed analysis. The Universal Transverse Mercator (UTM) projection was used for the analysis. Once the DEM was uploaded properly, the camera site data was prepared. The observation point was the location and height of the camera. All of the camera information was imported into ArcMap and projected into the correct coordinate system.

After all of the camera information was uploaded correctly into ArcMap the analysis of the DEM began. Given that a 30 m resolution DEM was used to analysis, it was substantially larger than the actual study area. In ArcMap a polygon shapefile was created and masked on top of the DEM. Therefore, the DEM was cropped to the size of the polygon. The DEM was converted from a raster file to a point file, so it would be easier to use in the future. Since a point file was created of the DEM, the area that is visible from the camera could be determined. Figure 4.2 shows the view of the KatKam webcam on the majority of days during the study period. The viewshed in the 3D Analyst Tools was used to determine the visible areas. Once the viewshed was completed a new layer was produced in ArcMap showing the visible and blocked areas.
Figure 4.2: View of the KatKam camera angle looking onto English Bay.

Target identification was the next step after all of the visible area was determined. ArcScene was used to identify the pre-selected targets. The pre-selected
targets are shown on a KatKam image in Figure 4.3 along with the targets distance from the camera. ArcScene was used to generate a scene using the results of the viewshed. ArcScene was used to identify the targets as there are tools to rotate, pan or zoom within a scene. Once the image in ArcScene looked like the KatKam photograph the targets were manually identified and the corresponding visible cells were found on the DEM in ArcMap. A shapefile was created with all of the targets that were located in the background. Attributes such as the line of sight distance from the camera, latitude and longitude, vertical and horizontal bearing, UTM coordinates and geographic coordinates of the pre-selected points were also calculated.

Figure 4.3: Target location and distance from the KatKam camera. Source: Telemark Systems, (2012) adopted by permission.

The line of sight distance was calculated using Equations (4.2) and (4.1). To calculate the line-of-sight distance, first the Euclidean distance was calculated from the camera. The Euclidean distance was calculated using the Proximity Point Dis-
tance tool in the ArcToolbox. The result was the distance from the camera to each of the control points. Next the elevation of each point above the horizontal plane was computed. The curvature of the earth and refraction were both accounted for when calculating the actual elevation above the horizontal plane. After each of the variables in Equation (4.1) were calculated Equation (4.2) was used to calculate the actual distance.

\[
Z_{\text{actual}} = Z_{\text{surf}} - \left( \frac{D^2}{\text{Diam. of the Earth}} \right) + R_{\text{refr}} \left( \frac{D^2}{\text{Diam. of the Earth}} \right)
\] (4.1)

- \(Z_{\text{actual}}\) = Actual elevation above the horizontal plane
- \(Z_{\text{surf}}\) = the elevation above mean sea level
- \(D\) = Euclidean distance between the camera and the target
- \(\text{Diameter of the Earth}\) = Defined as 12,740,000 m
- \(R_{\text{refr}}\) = Refractivity coefficient of light. Defined as 0.13

\[
\text{Act. Dist.} = \left( \left[ \text{Euclidean Dist.} \right]^2 + \left( \left[ \text{Actual Elev.} \right] - \left[ \text{Camera Elev.} \right] \right)^2 \right)
\] (4.2)

After calculating the line-of-sight distance the next task was to compute all of the visible cells’ geographic data from the DEM. The results of the viewshed analysis are used to identify the blocked and visible cells. The attribute data containing the blocked and visible cells was then joined to the DEM attribute table. Using the Spatial Analyst Tool in the ArcToolbox all of the visible cells were extracted from the DEM. The final DEM contained only the visible cells from the KatKam camera. The line-of-sight distance was computed for all of the visible points using Equation (4.2). Once all of the images were registered, the pixel intensity was taken from each of the images and a contrast ratios were calculated between the sky and each target using Equation (4.3).

\[
\text{ContrastRatio(\%)} = \frac{(\text{TargetIntensity} - \text{SkyIntensity})}{\text{SkyIntensity}}
\] (4.3)

73
Contrast ratios were calculated from pixel intensities each of the five targets. Contrast measurements can be used to estimate total extinction using a theoretical equation (Equation (4.4)). Where \( r \) is the distance to the target, \( C_r \) (apparent contrast) is the contrast of the target at distance \( r \) and \( C_o \) (inherent contrast) is contrast of the target at distance zero (Molenar et al., 2004). The theoretical equation to calculate extinction is shown in Equation (4.5).

\[
C_r = C_o \exp(-r * B_{ext})
\]  

(4.4)

The theoretical equation given in Equation (4.5) can be used to calculate extinction, however the theoretical \( C_o \) and \( r \) are not ideal and a statistical model were needed to estimate these parameters. Using the theoretical \( C_o \) and \( r \) is not ideal as the theoretical equation uses an estimated inherent contrast on the cleanest days and then applied in the extinction calculation on all calculations. \( C_o \) is influenced by solar geometry, the brightness of the target, time of day and cloud cover, therefore using the same \( C_o \) for all calculations allows for greater uncertainty in extinction calculations.

\[
B_{ext} = -1/r * \log(cr/Co)
\]  

(4.5)

For each target, a linear regression model was fitted to estimate \( r \) and \( C_o \) based on the training data set (randomly chosen set of days).

\[
\text{LinearRegressionModel} : \log(Cr) = A * B_{ext} + B
\]  

(4.6)

Hourly extinction values were subsequently estimated based on the regressed parameters (\( r \) and \( C_o \)) and theoretical equation using the testing data set (randomly chosen set of days). Estimated atmospheric extinction (\( B_{ext} \)) was calculated using Equation (4.7) and \( B \) is the slope and \( A \) is the y-intercept from a regression between a test and training set of days within the 2009 study period in the linear model (Equation (4.6)).
These estimated extinction values were verified with the observed optical measurements (nephelometer, NO2 analyzer and aethalometer) from 2009 in Abbotsford, British Columbia. Estimated extinction was compared to the observed extinction to determine the feasibility and comparability of the model for a particular target. To determine which model performed the best, the distribution of error based on historical data and the distribution of estimated \( B_{ext} \) was determined. The target with the smallest spread was then used to calculate visual range. Results could be sensitive to parameters such as the rounding of the diameter of the Earth and changing solar geometry throughout the day. All other parameters were calculating using the exact information relating to the camera location to decrease any sensitivity in the results.

Visual range was computed at each of the targets using Equation (4.8) and compared on smoke and non-smoke days for the available days in 2009.

\[
\text{Visual Range} = 3.9 / \text{Extinction Coefficient} \\
(4.8)
\]

## 4.4 Results and discussion

<table>
<thead>
<tr>
<th>Statistics</th>
<th>UBC</th>
<th>Bowen Island</th>
<th>Mount L.</th>
<th>Mount R.</th>
<th>Tree</th>
</tr>
</thead>
<tbody>
<tr>
<td>( r^2 )</td>
<td>0.1564</td>
<td>0.335</td>
<td>0.3158</td>
<td>0.1737</td>
<td>0.06</td>
</tr>
<tr>
<td>p-value</td>
<td>0.006526</td>
<td>2.516e-05</td>
<td>4.83e-05</td>
<td>0.003961</td>
<td>0.0003573</td>
</tr>
<tr>
<td>LM.RMSE</td>
<td>64.92</td>
<td>45.90</td>
<td>50.36</td>
<td>72.46</td>
<td>72.63</td>
</tr>
</tbody>
</table>

In total there were 19 smoke days and 35 non-smoke days within the summer of 2009 subset used to calculate extinction and visual range. A linear regression
model was used to calculated extinction at each of the targets (Equation (4.6)). Actual observed extinction values were compared to estimated extinction values at each target (Table 4.1). Estimated extinction values at the target located on Bowen Island were compared to observed extinction values in Abbotsford in Figure 4.4. Using Pearson’s correlation the forecasted extinction and the observed have an $r^2$ value of 0.335. The low correlation value is likely due to the fact that Abbotsford is located approximately 85 km southeast of the target on Bowen Island. Therefore, the air quality and visibility could be significantly different in the two locations likely causing larger differences in the calculated extinction at each of the targets when compared to the observed at Abbotsford. But regardless, the estimated extinction values for Bowen Island were most similar to observed at Abbotsford. The $r^2$ value for Bowen Island is likely due to the fact that the target is located in the middle of the image (least distortion) and the target is not located too close or too far away from the camera (20 km). Estimated extinction values had the most significant relationship with the observed extinction values. The target that performed the best (had the lowest root mean square error) was the target located on Bowen Island (Table 4.1) with Mount Left being the next acceptable target. The extinction values calculated at Bowen Island were most similar to observed extinction in Abbotsford. Atmospheric extinction and visual range was calculated at each of the targets. At the target located on Bowen Island, the average visual range decreased by 51% on smoke days (average VR on smoke days was 58 km and 118 km on non-smoke days). Additionally, the Mount Left experienced a decrease in visual range on average by 34% on smoke days (average VR on smoke days 59 km and 105 km on non-smoke days).
Figure 4.4: Estimated extinction determined from Equation (4.7) at the target on Bowen Island compared to observed extinction in Abbotsford, British Columbia.

Extinction values calculated using contrast determined from pixel intensity at each target has proven to be a useful too. There is a certain amount of uncertainty in the exploratory methods used. For example, some of the target intensities may not be looking at the exact same point on each image as due to the large camera movements that could not be corrected. Additionally, results from the certain targets such as the tree and UBC did not have reasonable results, which could be due to their close proximity to the camera and the variation in target intensity.
Figure 4.5 shows registered images with their calculated visual range and extinction values from two smoke and non-smoke days from the summer of 2009. Visually it is obvious that visibility was degraded on smoke days. For example, when looking at the registered image Figure 4.4a and comparing to Figure 4.4b it is apparent that the colour and contrast is diminished within the scene and the mountain range is not as clearly outlined. Therefore, it is clear that as the smoke event continues visibility is degraded through time and there is a buildup of particles visible in the lower atmosphere on 12 July 2009. Visual range was significantly lower on both of the smoke days in Figure 4.5. On 11 September 2009 (Figure 4.4d) which was a non-smoke day, the visual range was 232 km in comparison to the smoke day on 25 July 2009 the visual range was 58 km. Furthermore, extinction values were lower on non-smoke days and higher on smoke days, which was to be expected. Additionally, just from visually interpreting these digital images during the smoke event it is clear air quality is degraded.
**4.5 Conclusions**

Visual range decreased on average by 60 km on smoke days, while extinction values increased. Results from this research show an increase in particles during smoke events in the lower atmosphere, decreasing visual range. Methods used to calculate visual range and extinction proved to be useful to determine which targets on a digital image most accurately calculate extinction. The target located on Bowen Island (center of the image) produced the most accurate results. Calculat-
ing visibility at targets located in the center of the image would be recommended in the future. Shortcomings were identified with technique, the results showed a consistent and significant decrease in visibility during smoke events. This was evident from both a visual examination of the images and from the automated calculation of visual range.

Based on this preliminary analysis, image metric and registration techniques used throughout this chapter can be applied to cameras in remote areas that do not having pollutant monitoring stations. This method could be used anywhere with visible black targets in the distance. Image registration methods have been semi-automated and can be transferred to other cameras. From this research it was found it is best to use digital images that do not experience large amounts of movement in the vertical and horizontal direction. In future research, it would be best to use a camera system that is set up for the purpose of calculating visibility. Image registration does correct for movements in the vertical and horizontal but only to a certain extent. From digital images, pixel intensity can easily be extracted from targets in the scene. Pixel intensity can be used to calculate contrast and then eventually an estimated extinction value can be developed. Observed extinction values in the Georgia Basin airshed were only available for the summer of 2009, therefore limiting the model created and the comparison between observed and estimated extinction. Additionally, there may have been a better relationship if the digital images were analyzed every hour instead of three times a day. Regardless, visual assessments of visibility and visual range values clearly show the degradation of air quality during forest fire smoke events and digital images can be used to assess visibility. Furthermore, this model was a good tool to determine which targets in a scene best represent the actual extinction.
Chapter 5

Conclusion

5.1 Summary of results

Several different tools were used to determine how air quality and visibility were influenced by forest fire smoke events in southwestern British Columbia. During forest fire smoke events, air quality was significantly degraded. The meteorology and complex terrain within the LFV makes the region susceptible to pollution episodes during the summer months. From this study, it is apparent that smoke from forest fire further decreases air quality in the region. The findings of this research can be applied to air quality forecasts and to the AQHI to help better inform the public. Additionally, the results give insight significant on the transport of smoke produced by forest fires over long distances. Methods and tools used to determine the air quality and visibility in this research can be applied to other regions of complex terrain around the world and areas in which air quality is degraded due to forest fire smoke. The objectives stated previously in Chapter 1 are re-visited below:

1. Determine the source of the majority of pollutants in the LFV.

NOAA’s HYSPLIT was utilized to help determine where the air parcels were transported from to YVR on smoke days. HYSPLIT back-trajectories were computed for each of the smoke days to determine interannual variation. Furthermore, HYSPLIT was used to determine how much cross-border trans-
port was experienced each summer. Up to 60% of trajectories during smoke periods were transported from the south into Canada. Each year varied in total number of smoke days and regional sources of smoke. For example, during the fire season of 2010 the majority of smoke was transported to the Georgia Basin from forest fires located in northern British Columbia. Whereas, the summer of 2008 smoke was primarily transported from the United States (south) into southwestern British Columbia. Additionally, forest fire smoke was transported to the Georgia Basin airshed from up to a 1000 km away in some instances. Determining where the majority of pollutants were transported from during smoke events is important for meeting air quality standards and improving air quality forecasting as smoke from thousands of kilometers can degrade air quality. In other regions influenced by forest fire smoke, it would be recommended to use HYSPLIT in the future to determine where the smoke particles have been transported from, which will also assist in assessing air quality.

2. To examine whether there is interannual variability in PM$_{2.5}$ and O$_3$ concentrations during forest fire smoke events.

After a thorough analysis of average daily PM$_{2.5}$ and maximum daily O$_3$ at twelve monitors across the Georgia Basin, it was determined that concentrations of both increase significantly during smoke events. PM$_{2.5}$ increased on average by 4.45 $\mu$g m$^{-3}$ and O$_3$ by 7 ppb during smoke events. Understanding how much concentrations of PM$_{2.5}$ and O$_3$ increase during forest fire smoke events is important as significant increases are known to have adverse health impacts. Further, knowing how much PM$_{2.5}$ and O$_3$ increase during smoke events can help improve air quality forecasts and informing the public about reduced air quality. A weather typing catalog was used to determine the smoke and non-smoke subsets and found that on smoke days from 2008-2011 two weather patterns dominated in the LFV. The first weather pattern had a ridge of high pressure on the Pacific and in the LFV winds were coming from the northeast. Weather patterns such as this with winds from the northeast are likely to transport pollutants from the interior and northern parts of British Columbia into the Georgia Basin airshed. Characteristics of
the second dominant weather pattern include, a ridge of high pressure is located over the west coast, producing light winds, sunshine and subsidence. The second dominant weather pattern is known to produce poor air quality within the LFV and produces favourable conditions to produce forest fires (warm, dry). The weather catalog was useful in determining the weather types which dominate on smoke days, as this information can be used to better predict air quality in the future during smoke events in the LFV. Determining the dominant weather patterns during smoke events is important as it gives insight on the role synoptic weather patterns play on the transport and dispersion of pollutants, especially since these weather patterns are likely to increase in frequency in the future.

3. To automate the calculation of visibility using digital images.

This study used exploratory methods to semi-automate the calculation of visibility using digital images. Image metrics were used to align and register all of the images. Part of the registration was done automatically, while further correction was done using a semi-automatic method. Methods used to register and align the images could be automated if the set of images does not move significantly in the vertical and horizontal direction. In future work, using a digital camera that is monitored and set up for the purpose of calculating visual range would be recommended.

Once the KatKam images were registered and aligned, pixel intensity was extracted to calculate contrast on each image. Using the contrast values, estimated extinction values were created and compared to observed extinction values. Furthermore, five different targets were used to calculate contrast and extinction. Each of the targets was evaluated on their ability to calculate extinction to determine which target performed the best. The methods used to determine which target performed the best are important to produce the most accurate estimated extinction values. Studies such as this can be easily applied to other digital cameras as a method to calculate extinction for a reasonable cost. Given that the methods used to calculate visual range were exploratory methods, with some tailoring these methods could be applied to regions with black targets visible in the distance. Digital images are an
easy way to display and inform the general public about degraded air quality during forest fire smoke events.

4. To determine how visibility is degraded during forest fire smoke events.

Through the investigation of visual range during the summer of 2009, it was concluded that visual range was decreased on average by 60 km during smoke events in the Georgia Basin airshed. Koshmieder’s formula was used to calculate visual range. Bowen Island was the target that performed the best on the KatKam images, on non-smoke days the visual range on average was 118 km and 58 km on non-smoke days. Extinction values calculated from the digital images had lower values on non-smoke days and higher on smoke days, which is to be expected. Understanding how much visual range is reduced during forest fire smoke events is important for economic and aesthetic reasons. The summer months are busy months for tourism in Vancouver and southwestern British Columbia, degraded visibility would have a negative impact on visibility as many tourists come to see the mountainous scenery. Errors associated with the results produced by the other targets could be related to the registration methods, the darkness of the target, and distance from the target to the camera or the automatic adjustment the camera does at dawn and dust each day. Regardless, these methods could be used to calculate visual range and extinction at a reasonable cost. The use of digital images to calculate visual range makes it easier to associate poor quality with an actual observed value.

5. To examine the extent to which forest fire smoke impacts air quality and visibility.

Air quality and visibility were significantly degraded during smoke events from 2008-2011 in the Georgia Basin airshed. SFD displayed forest fires located in northwestern United States, northern and eastern British Columbia and Alberta influencing air quality in the region. Concentrations of PM$_{2.5}$ and O$_3$ increased during smoke events at all monitors. Certain monitors experienced higher increases in PM$_{2.5}$ and O$_3$ depending on their geographic location. The presence of forest fire smoke in the LFV is also influenced by
synoptic weather patterns. In the Georgia Basin, during the summer months the dominant weather patterns tend to either produce conditions which are favourable for producing forest fires or conditions that are likely to transport smoke into the airshed. Visual range and extinction were both negatively impacted during smoke events during the examination of the 2009 fire season. Visual range was decreased on average by 51% on smoke days. Overall, it is clear from this study that both air quality and visual range were negatively impacted by forest fire smoke during the fire seasons from 2008-2011.

5.2 Future research outlook

With our changing climate, there is abundant research in regards to air quality monitoring and regulation. There is a constant need to continuously monitor pollutants such as PM$_{2.5}$ and O$_3$ within the LFV. Continued monitoring of pollutants throughout the LFV is essential to improving and regulating air quality. Without the monitoring network within the LFV none of this research would have been possible. To further this research observations of organic carbon should be investigated to help better understand the properties of the smoke plumes influencing air quality in the LFV. Furthermore, with concentrations of PM$_{2.5}$ and O$_3$ significantly increasing during forest fire smoke events, it seems necessary to account for these increases into Canada’s Air Quality Health Index (AQHI). Additional work could be conducted investigating how much concentrations of O$_3$ increase during smoke transport events regionally and globally.

SFD is a useful tool to track smoke plumes and forest fire locations. With continued improvements of this tool satellite images will assist in better forecasting air quality during smoke events. SFD can also be used as a tool to inform the public of areas being impacted by smoke from forest fires. NOAA has already made improvements to include the density of the smoke plume. There is great value to having access to such a large satellite archive.

It would be useful to continue this research by improving the techniques used to calculate visibility with digital images. Digital images could easily be used to calculate visual range with some re-working of the methods and a reliable set of images. In the future it would be best to use a camera which does not move
much in the vertical and horizontal direction. Another improvement to the visibility methods could be to determine visibility for the entire duration of the day (during daylight hours) rather than at three different times of the day. Furthermore, continuous monitoring of pollutants and extinction is important to assist in assessing the reliability of digital images to calculate visibility.
Bibliography


CCME. Canada Wide Standards For Particulate Matter(PM) and Ozone, June 2000. URL http://www.ccme.ca/assets/pdf/pmozone_standard_e.pdf. Date Accessed: 06/25/2012. → pages 6


EPA. Air quality criteria for particulate matter., 1996. → pages 2


D. Jaffe, D. Chand, W. Hafner, A. Westerling, and D. Spracklen. Influence of fires on O3 concentrations in the western US. *Environmental science & technology*, 42(16):5885–5891, 2008a. → pages 1, 4, 6, 39, 47, 64

88
D. Jaffe, W. Hafner, D. Chand, A. Westerling, and D. Spracklen. Interannual variations in PM2.5 due to wildfires in the western United States. *Environmental science & technology, 42*(8):2812–2818, 2008b. → pages[1,2,3,5,7]


