Wintertime PM10 measurements and modelling in Alexandra and Mosgiel, Otago, New Zealand.

Amber Tate

A thesis submitted for the degree of

Master of Science

at the University of Otago, Dunedin, New Zealand.

December 2010

Abstract

Particulate air pollution from domestic sources adversely affects wintertime air quality in many small towns in New Zealand, particularly in the south. Low air temperatures warrant the use of domestic heating appliances, and during calm conditions, the emissions released by these appliances stagnates in the near surface atmosphere. This is exacerbated in towns that are topographically constrained, as sheltering from synoptic winds occurs and light drainage flows develop instead, leading to the development of temperature inversions, and high air pollution levels as a result.

Alexandra, Central Otago, and Mosgiel, in eastern, coastal Otago are two such towns, and because of their air pollution history, and a relative paucity of knowledge of their air pollution meteorology, were the focus of this research. The research aims were to investigate the air pollution meteorology of each town through observational point source data, before numerical modelling was employed to gain further insight into these processes, both horizontally and vertically. The suitability of the current location of the Otago Regional Council (ORC) monitoring sites was reviewed, and the final aim was to determine the necessary percentage reduction in emissions for each town in order to reach the standards set be the National Environmental Standard (NES) for air quality. Three years of meteorological and PM10 data were analysed before selecting the winter of 2008 for modelling, using The Air Pollution Model (TAPM).

TAPM was run from 1 May to 31 August for each town and was found to correctly predict daily PM10 concentrations 66% of the time in Alexandra and 71% of the time in Mosgiel, in terms of breaches and non-breaches of the NES. At a daily scale, TAPM was able to simulate diurnally switching thermal winds in the Alexandra basin, and reproduced both the location and magnitude of highest pollution concentrations over a 10 day case study. Drainage flows were also modelled well in Mosgiel, and temperature inversions were simulated in both towns, although with no vertical observational data to test the vertical modelled data against, these must be treated with some caution. TAPM also simulated in considerable detail the spatial variability of the wind regime, both horizontally and vertically. This research has shown that neither of the ORC monitoring sites is currently located in the area of worst air quality, which is a requirement of the NES. However, the percentage reductions in emissions required to meet the NES could not be calculated.

This research has shown that TAPM is a useful tool for simulating meteorological and air pollution processes, and is potentially a valuable asset for air pollution management. Selecting the parameters in the model set-up that will reflect the conditions of the study site most closely will improve model performance, thus, providing a second and third dimension to existing point source datasets.

Acknowledgements

This thesis would not have been possible without all the help I received along the way. In particular I would to thank the following people.

First and foremost, special thanks go to my two supervisors, Dr Rachel Spronken-Smith and Dr Nicolas Cullen for all your encouragement, support, and feedback.

The Otago Regional Council for the use of the observational meteorological and PM10 data, and Deborah Mills at the Council for answering numerous questions.

Dr Peyman Zawar-Reza at the University of Canterbury, for coming down to Dunedin to help with TAPM, and for answering numerous questions regarding the intricacies of the model.

Also to Jono Conway for helping me make sense of TAPM in the beginning.

David McDowall for getting the modelling lab up and running.

Owen West for the use of your Alexandra AWS data.

Ross Marsden at the MetService for providing the synoptic charts.

Alice Bowden for many a good chat about TAPM, and science in general.

Table of Contents

Abstract……...ii
Acknowledgements……………………………………………….………………iii
Table of Contents……………………………………………………………….iv
List of Figures…………………………………………………………………….vii
List of Tables……………………………………………………………………x

Chapter 1: Introduction………………………….……………………………....1
1.1 Introduction………………………………………………………………….1
1.2 Definitions and Legislation……………………………………………….……1
1.3 Rationale…………………………………………………………………….3
1.4 Research Aims and Thesis Structure………………………………………..4

Chapter 2: Literature Review……………………………………………………5
2.1 Introduction……………………………………………………….……………5
2.2 A Brief History of Air Pollution…………………………………………………….5
2.3 Health Effects………………………………………………………………7
2.4 Scales…………………………………………………………………………..9
2.5 Components of Air Pollution……………………………………………………10
2.5.1 Emissions……………………………………………………………...10
2.5.2 Sate of the Atmosphere………………………………………………..11
2.5.3 Thermal Circulations…………………………………………………….15
2.6 The Meteorological Context for Air Pollution in New Zealand…………….…….18
2.7 Air Pollution in the South Island………………………………………………..20
2.7.1 Alexandra……………………………………………………….……..21
2.7.2 Mosgiel……………………………….…………………….…………22
2.8 Air Pollution Modelling……………………………………………………………23
2.9 Summary…………………………………………………………………….…..26

Chapter 3: Methods…………………………………………………………….28
3.1 Introduction…………………………………………………………………...…28

3.2 Physical Setting……………………………………………………………….28
3.2.1 Alexandra…………………………………………………..…………28
3.2.2 Mosgiel……………………………………………………………….29
3.3 Overview of Research Methods……………………………………………...…30
3.4 Observational Methods…………………………………………………………31
3.4.1 Observational Data……………………………………………………31
3.4.2 Observational Data Analyses…………………………………………35
3.5 Modelling Methods……………………………………………………………...35
3.5.1 Model Description……………………………………………………35
3.5.2 Model Set-up…………………………………………………………36
3.5.3 Model Validation……………………………………………………………...40
3.6 Summary………………………………………………………………………...41

Chapter 4: Observational Results…………………………………………………...42
4.1 Introduction……………………………………………………………………….42
4.2 Alexandra……………………………………………………………….....…..42
4.2.1 Trends in PM10, 1999 – 2009………………………………………...42
4.2.2 Climatic and Air Pollution Trends, 2007 – 2009………………………..44
4.3Mosgiel…………………………………………………………………….……47
4.3.1 Trends in PM10, 1999 – 2009………………………………………...47
4.3.2 Climatic and Air Pollution Trends, 2007 – 2009………………………..47
4.4 Summary………………………………………………………………………...50

Chapter 5: Modelling Results……………………………………………………52
5.1 Introduction…………………………………………………………………......52
5.2 Alexandra………………………………………………………………………..52
5.3Mosgiel…………………………………………………………………….……57
5.4 Summary of Model Performance………………………………………………..60
5.5 Case Study One: Alexandra, 21 – 30 June 2008……………………………......60
5.6 Case Study Two: Alexandra, 23 August 2008…………………..………………..65
5.7 Case Study Three: Mosgiel, 23 August 2008…………………………..….…….70
5.8Summary…………………………………………………………………….…...77

Chapter 6: Discussion…………………………………………………………………78
6.1 Introduction……………………………………………………………………......78
6.2 Summary of ModePerformance…………………………………………………..78
6.2.1 Air Temperature………………………………………………………………78
6.2.2 Wind Speed and Wind Direction……………………………………………...81
6.2.3 PM10 Concentrations…………………………………………………………83
6.2.4 Synoptic Considerations………………………………………………………84
6.3 Limitations………………………………………………………………………….85
6.3.1 Observational Meteorological Data…………………………………………...85
6.3.2 Emissions Data……………………………………………………………….86
6.3.3 Modelling Limitations………………………………………………………...88
6.4 Implications for Achieving the NES……………………………………………….89
6.5 Alternative Measures for Reducing PM10 Air Pollution………………...………92
6.6 Summary…………………………………………………………………………...94

Chapter 7: Conclusion…………………………………………………………...……96
7.1 Introduction……………………………………………………………………......96
7.2 Summary of Key Findings……………………………………………………......96
7.3 Recommendations for Future Research……………………………………..……..98
7.4 Concluding Thoughts………………………………………………………….......99

References……………………………………………………………………………...100
Personal Communications………………………………………………………….....105
Appendix A……………………………………………………………………...…106
Appendix B……………………………………………………………………………...107

List of Figures

Figure 2.1 The respiratory system…………………….……………………………...7

Figure 2.2 Time and space scales of a variety of atmospheric phenomena…………..…...10

Figure 2.3 A lapse profile shows temperature decreasing with height which
allows dispersion of pollutants through convective mixing………………..………...12

Figure 2.4 The daily cycle of dispersion of atmospheric pollutants in
relation to atmospheric stability……….……………………………………….……...13

Figure 2.5 The daily cycle of boundary layer growth and erosion under
anticyclonic conditions..…………………………………………………………….…14

Figure 2.6 Slope winds…………………………………………………………...16

Figure 2.7 Mountain-valley winds……………………………………………….17

Figure 2.8 Topographical maps of Alexandra and Mosgiel…………………………...22

Figure 3.1 Map of the South Island showing the locations of Alexandra
and Mosgiel………………………………………………………………..….............29

Figure 3.2 Locations of the monitoring sites for Alexandra and Mosgiel…………….…32

Figure 3.3 View of the filter tape inside the BAM………………………...………..32

Figure 3.4 The Alexandra monitoring site and the Mosgiel monitoring site……….…33

Figure 3.5 Locations of the three sites from which meteorological data
Were obtained in Alexandra…………………………………..……….……………33

Figure 3.6 Emissions profiles for Alexandra and Mosgiel……………………...…..39

Figure 4.1 Number of breaches and number of days sampled per year from
1999 - 2009 for Alexandra……………………………………………………......…43

Figure 4.2 Daily average PM10 levels for Alexandra from 2007 - 2009……….........43

Figure 4.3 Monthly ensembles for temperature, wind speed, and PM10
for Alexandra and Mosgiel from 2007 - 2009……………………………………....44

Figure 4.4 Scatterplots of daily averaged PM10 versus temperature, and
PM10 versus wind speed for Alexandra from 2007 - 2009…………………..……..46

Figure 4.5 Wind roses for Alexandra from ORC data from 2007 - 2009……………...46

Figure 4.6 Diurnal ensembles for 149 high pollution days in Alexandra and 20 high pollution days in Mosgiel from 2007 - 2009……………………...…..47

Figure 4.7 Number of breaches and number of days sampled per year from 2001 - 2009 for Mosgiel…………………………………………………………48

Figure 4.8 Daily average PM10 levels for Mosgiel from 2007 - 2009…………….......48

Figure 4.9 Scatterplots of daily averaged PM10 versus temperature, and PM10 versus wind speed for Mosgiel from 2007 - 2009……………………….…......49

Figure 4.10Wind roses for Mosgiel from ORC data from 2007 - 2009………….……49

Figure 5.1 Time series of observed versus modelled hourly temperature, wind speed, and PM10 for Alexandra for the winter of 2008. ……………………….….54

Figure 5.2 Diurnal temperature ensemble for high pollution days correctly modelled by TAPM…………………………………………………………...……56

Figure 5.3 Diurnal PM10 ensemble for high pollution days correctly modelled by TAPM…………………………………………………………………....56

Figure 5.4 Time series of observed versus modelled hourly temperature, wind speed, and PM10 for Mosgiel for the winter of 2008……………………..…..58

Figure 5.5 Synoptic situation for 21 June, 24 June, 27 June, and 30 June 2008 at 1200 hours NZST……………………………………………………………...61

Figure 5.6 Time series of observed and modelled PM10 and observed and modelled temperature for 21 - 30 June 2008 in Alexandra…………………………....61

Figure 5.7 Time series of observed and modelled wind speed and wind direction for 21 - 30 June 2008 in Alexandra…………………………………………62

Figure 5.8 Measured PM10 concentrations versus modelled PM10 concentrations for 21 - 30 June 2008 in Alexandra……………………….…..…….……64

Figure 5.9 Synoptic situation for 23 August 2008 at 0000 hours and 1200 hours NZST……………………………………………………………………….…65

Figure 5.10 Time series of observed and modelled PM10 and observed and modelled temperature for 23 August 2008 in Alexandra.………………………....66

Figure 5.11 Time series of observed and modelled wind speed and wind direction for 23 August 2008 in Alexandra.…………………………………………...66

Figure 5.12 Vertical profiles of potential temperature, wind speed, and wind direction on 23 August 2008 in Alexandra……………………..………………..68

Figure 5.13 GIS visualisation from TAPM showing wind speed, wind direction, and pollution concentrations at three hour intervals on 23 August 2008 in Alexandra……………………………………………………………..69

Figure 5.14 Time series of observed and modelled PM10 and observed and modelled temperature for 23 August 2008 in Mosgiel……………………………71

Figure 5.15 Time series of observed and modelled wind speed and observed and modelled wind direction for 23 August 2008 in Mosgiel……………......71

Figure 5.16 Vertical profiles of potential temperature, wind speed, and wind direction on 23 August 2008 in Mosgiel………………………………………..73

Figure 5.17 GIS visualisation from TAPM showing wind speed, wind direction, and pollution concentrations at three hour intervals on 23 August 2008 in Mosgiel…………………………………………………………….…74

Figure 5.18 Measured PM10 concentrations versus modelled PM10 concentrations for 23 August 2008 in Mosgiel……………………………….…......76

Figure 6.1 Decoupling of the atmosphere within a basin from the over-riding synoptic situation due to cold air drainage………………………………..84

List of Tables

Table 3.1 Sensitivity analysis for determining model parameters for Alexandra for May 2008……………………………………………………………….37

Table 3.2 Data assimilation set-up…………………………………………………..37

Table 5.1 Summary and validation statistics for observed and modelled temperature, wind speed, and PM10 for the winter of 2008 for Alexandra…………...53

Table 5.2 Model accuracy for correctly predicting breaches and non-breaches of the NES for PM10 in Alexandra……………………………………..55

Table 5.3 Summary and validation statistics for observed and modelled temperature, wind speed, and PM10 for the winter of 2008 for Mosgiel…………..…..57

Table 5.4 Model accuracy for correctly predicting breaches and non-breaches of the NES for PM10 in Mosgiel………………………………………..59

Table 5.5 Summary and validation statistics for observed and modelled temperature, wind speed, and PM10 for 21- 30 June 2008 in Alexandra……….…….63

Table 5.6 Summary and validation statistics for observed and modelled temperature, wind speed, and PM10 for 23 August 2008 in Alexandra……….………67

Table 5.7 Summary and validation statistics for observed and modelled temperature, wind speed, and PM10 for 23 August 2008 in Mosgiel…………………72

1

Introduction

1.1 Introduction

Air pollution has occurred throughout human history as a by-product of our activities. As a result, human health is compromised, as is the health of the environment that we live in and rely on for our survival. It is of paramount importance therefore, that we protect our environment and ourselves so that we, as a species, can continue to exist into the future. This research investigates the air pollution meteorology of two towns in Southern New Zealand through observations and numerical modelling. The aim of this chapter is to introduce this research by providing information on the definitions and current legislation regarding air quality in New Zealand. The rationale for conducting this research will also be put forth. Following this, the research aims will be presented, before finishing with an overview of the structure of the thesis.

1.2 Definitions and Legislation

Air pollution can be divided into two broad categories: gaseous based pollutants and particulate based pollutants. Particulates, or small particles, in the atmosphere of all sizes and from all sources are categorised as total suspended particulates (TSP). Historically, air quality was measured solely by levels of TSP. However, it is now understood that the finer particles within TSP are responsible for damage to human health; this finer fraction is caused mainly by anthropogenic activity such as emissions from combustion, industrial processing, and construction related surface disturbance (Oke, 1987). As a result of this, TSP has been divided into several categories. The first of these is particulate matter less than ten microns in diameter (PM10); this is the level at which guidelines have been set in New Zealand. Internationally, North America and Europe have legislation regarding PM10, but also have legislation regarding particulate matter less than 2.5 microns in diameter (PM2.5) as well. There is also evidence that it may be beneficial to have a PM1 threshold because of the large proportion of particulates less than one micron in diameter within the PM2.5 fraction (Geller et al., 2004; Monn et al., 1995).

A National Environmental Standard (NES) for air quality in New Zealand was introduced in 2004 under the Resource Management Act 1991, and came into force on September 1 2005. Under the NES, the maximum amount of PM10 allowed is 50 micrograms of particulate per cubic metre of air (50 µg m^{-3}) on average for every 24 hour period, with one possible exceedance per year. The deadline for achieving the NES is 2013. Regions are divided into airsheds based on their air pollution potential and history; for those airsheds that currently breach the NES, regional councils are responsible for continuous monitoring of PM10 in order to ensure that the standard is met. If, by 2013, the standard has not been met, councils will be unable to grant any resource consent application that requires PM10 discharges to the air (Ministry for the Environment, 2010; Otago Regional Council, 2005). Regional Councils are also recommended to develop straight line paths (SLiPs) or curved line paths (CLiPS) in order to reach the NES. A SLiP begins with an annual average maximum value (which is an average of the past five years) and ends at the set value of 50 µg m^{-3}. The line (or curve) between these two values indicates the reductions needed year by year in order to reach the target. These values are based on emissions rather than concentrations, as local meteorology can have a confounding influence (Fisher et al., 2005).

The NES for air quality has also set standards for wood burners, which include emissions of no more that 1.5 grams of particulate per kilogram (g kg^{-1}) dry wood burnt and a thermal efficiency of at least 65%. These criteria have been incorporated into the Otago Air Plan, with all wood burners installed after 2004 and on a section smaller than two hectares being required to comply by these standards. Further to this, for any new wood burners being installed in Air Zone 1 airsheds, (which have the worst air quality) the emission level has been reduced further to 0.7 g kg^{-1}. Older burners that emit more than 1.5 g kg^{-1} are able to be used until 1 January 2012, after which time they will be banned (Otago Regional Council, 2009a).

1.3 Rationale

Research has found that long-term exposure to low levels of air pollution results in greater negative health effects than short-term exposure at higher levels, although exposure at any level can be harmful. In New Zealand, air pollution is associated with 900 deaths per year in those aged over 30, with approximately one third of these deaths coming from domestic emissions. Air pollution is also associated with 1500 cases of chronic bronchitis and almost two million restricted activity days. The total cost to the country for these is estimated at $1139 million per year. These figures exclude natural sources of air pollution such as sea spray, wind blown dust, and pollen, as these are largely beyond human control (Fisher et al., 2007).

Many New Zealand towns, and particularly in the South Island, have air pollution problems during the winter months due to the use of domestic heating appliances which emit particulates into the atmosphere. In Central Otago towns, where domestic emissions are responsible for elevated levels of air pollution, a survey carried out by the Otago Regional Council (ORC) revealed that 98% of the 836 participants were aware that they had an air pollution problem. Eighty-eight percent thought that something should be done about the problem, and 54% (the most popular answer) thought that better health would be the main benefit of having cleaner air. In Central Otago towns, enclosed wood burners are the main form of heating used, although more than one form is generally required due to the low temperatures experienced there during the winter months (Otago Regional Council, 2006).

The two towns of Alexandra and Mosgiel both suffer from poor air quality in winter, with consistent breaches of the NES. Research into the processes that cause poor air quality is limited in both towns, although some spatial data does exist. The existing data will be used as a platform from which this research will build on. Meteorological and PM10 data also exist for both towns but these provide point source values only with no spatial variability, either in the horizontal or vertical. A few studies have explored spatial variation in PM10 in these towns using mobile observations, but numerical modelling is a tool that can provide further insight into processes influencing poor air quality. By utilising numerical modelling, both PM10 and meteorological variables can be explored in three dimensions.

1.4 Research Aims and Thesis Structure

The key aims of this research are to:

- Investigate the air pollution meteorology of Alexandra and Mosgiel through point source observational data.
- Use numerical modelling to gain insight into spatial and temporal trends in PM10 concentrations and meteorological processes contributing to poor air quality.
- Determine whether the current ORC monitoring sites are in the area of worst air quality for each town.
- Calculate the necessary percentage reduction in emissions required for each town so that the NES can be achieved.

This thesis will consist of seven chapters. Chapter Two will review the literature and provide background information on the history, health effects and causes of air pollution, as well as setting the meteorological context for air pollution in New Zealand, and specifically the two Otago towns of Alexandra and Mosgiel. The Air Pollution Model (TAPM) will be introduced and air pollution modelling studies in New Zealand reviewed. In Chapter Three the physical setting, land use and climate of the two towns will be outlined. The methods used for data collection and analysis will also be provided, including the model set up and sensitivity analysis. In Chapter Four, an overview of the results for the observational data will be presented, and the modelling results will be presented in Chapter Five. Chapter Six will interpret the key findings of this research and link these back to the research aims before conclusions are presented in Chapter Seven.

2

Literature Review

2.1 Introduction

The amount of air pollution at any given place is determined by the nature of the emissions and the state of the atmosphere (Oke, 1987). The state of the atmosphere is controlled by the overriding synoptic circulation patterns, the local thermal circulation patterns, and surface energy balances. Once polluting substances are released into the atmosphere, they have the potential to cause damage to humans, animals and vegetation. In this chapter, these processes will be explained. To begin with, a brief history of air pollution will be presented, followed by the health effects of exposure to air pollution. Emission characteristics and atmospheric controls will then be detailed. The context for air pollution in New Zealand will be discussed and the two towns of Alexandra and Mosgiel will be introduced. The chapter will conclude with a review of air pollution modelling studies.

2.2 A Brief History of Air Pollution

Domestic wood burning in Rome and copper smelting for coin production in both Rome and China were common sources of air pollution in the early ages (before 1200). By the Middle Ages (1200-1700) the heating of limestone to use as a cement-like building material was a major source of air pollution. As the wood used to heat the limestone became more scarce, it was replaced with “sea coal” (so named because it was abundant along the northeast coast of Great Britain (Blewett, 1998)), which generated even more air pollution. Due to this, a commission was set up as early as

1285 in an attempt to curb air pollution levels. However, sea coal continued to be used not only in lime kilns, but also for the construction of glass and bricks, in breweries and for home heating (Jacobson, 2002).

Air pollution worsened through the eighteenth century in Great Britain as coal continued to be used, and by this time the steam engine was a major contributor. By the nineteenth century, the use of the steam engine in other parts of the world including Europe, the United States, Japan, India and South Africa created widespread air pollution problems. In Great Britain and the United States, the air pollution problem had become so severe by the 1940s that several bills were brought to Parliament, though initially with limited success (Jacobson, 2002).

In December 1952, the London smog outbreak occurred and was responsible for 4000 excess deaths. This was caused by heavy emissions of coal and other materials in the presence of fog and temperature inversions. Deaths occurred in all age groups but were greater for those aged over 45, and 80% of those who died had pre-existing heart or respiratory problems (Jacobson, 2002). Many of those who fell ill during the outbreak recovered temporarily but died months or years later from the lingering effects of this air pollution event (Blewett, 1998). During this outbreak, peak concentrations were estimated to be around 4460 $\mu g\ m^{-3}$, and the streets of London were said to be dark at midday (Jacobson, 2002). Other air pollution disasters occurring around this time include those in the Muese Valley, Belgium, which resulted in 60 deaths in 1930, and Donora, Pennsylvania, which resulted in 20 human deaths and almost 1000 animal deaths in 1948 (Blewett, 1998). At around the same time Los Angeles was also suffering from smog, but in this case it was a photochemical smog caused by emissions undergoing a chemical reaction in the atmosphere (Zawar-Reza & Spronken-Smith, 2005).

During the time these air pollution events were occurring, regulations remained weak as the industries responsible for much of the emissions held political power to resist intervention, and argued that tighter regulations would stunt economic growth. The long-term health effects of exposure to air pollution were also still largely unknown at this time. Despite this, the United States implemented the Air Pollution Control Act in

1955 and the United Kingdom did the same with the U.K. Clean Air Act of 1956 (Jocobson, 2002).

2.3 Health Effects

When looking to the effects of air pollution on human health, the focus is on PM10, as this fraction of TSP is able to be inhaled and then cause respiratory and cardiovascular problems. With respiratory illness as the fourth most common illness suffered by humans, the right to experience the benefits of clean air is of particular concern. Inhalation is a major route for toxic materials to enter the body, and because people cannot choose the quality of the air they breathe, exposure to polluted air often results in respiratory illness, especially in the work place (Koenig, 2000).

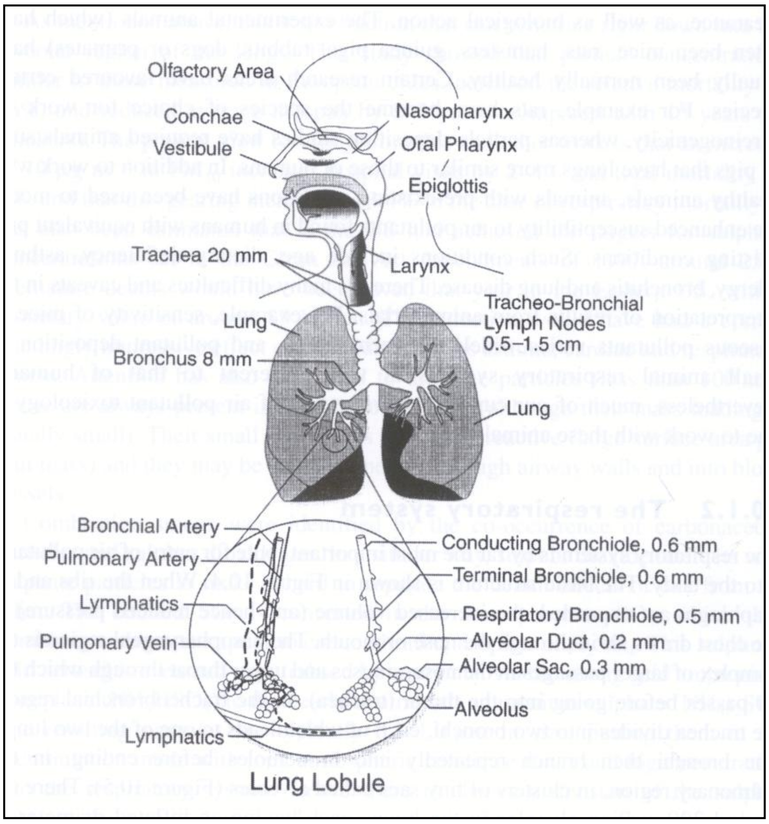

Figure 2.1 The respiratory system. Source: Colls, 2002, p396.

Once air is inhaled through the nose or mouth it travels down the trachea which then divides into two bronchi, one leading to each lung. Each bronchus branches repeatedly into bronchioles which end in alveoles, which is where gas exchange occurs (Figure 2.1). Most internal surfaces of the respiratory tract are lined with minute cilia which move in unison to continuously remove trapped material, however, there are no cilia in the alveoles (Colls, 2002).

The nose is the first defence against polluted air; inhaled particles greater than 10 µm in aerodynamic diameter are deposited there either by inertial impaction or by interception on the hairs in the nasal passages, or on the walls of the nose, sinuses and throat. Particles less than 10 µm in aerodynamic diameter however, are able to penetrate into the bronchi and the lower respiratory tract. The diameter range between 0.1 µm and 1.0 µm tends not to be deposited as these particles are too small to impact or diffuse to the walls and may penetrate deep into the lung but are often exhaled again before they can be deposited. As a result, atmospheric loadings of this size range are greater (Colls, 2002).

Once particles enter the body, their removal can occur in several ways. The most simple and instantaneous of these is by coughing, which creates enough pressure to expel particles from the lungs (Koenig, 2000). Alternatively, particles that are deposited in the breathing passages are transported by the cilia to the throat where they are ingested. This also occurs in the lower respiratory tract but the distance to the trachea is further and the rate of movement slower; the clearance time here is between a few hours and a day, with clearance rates dropping sharply after one day. Particles which have penetrated into the alveolar region of the lung where there are no cilia are cleared on a time scale of months. These particles are either dissolved or engulfed by mobile cells which then remove themselves from the lung. However, if there are many particles, these mobile cells can be overwhelmed. There is also evidence that other organs can be affected, such as the heart and brain which may experience blood clots caused by excess coagulation because of inflammation initially caused by the presence of the particles (Colls, 2002).

Children, elderly, and those with pre-existing diseases such as asthma are most at risk (Boubel et al., 1994). Children are a vulnerable population because they inhale and retain more air pollution than adults per unit body weight. The development of their organs can be hindered by exposure to air pollution at critical periods. As children spend more time outdoors than adults, they are exposed more; this time is often spent playing or being physically active, which also increases exposure to pollutants through increased respiration. The elderly are also a vulnerable population as they are often more frail, and have been exposed to air pollution for longer. They are also more likely to have pre-existing illnesses that will make them more susceptible to being affected by air pollution. There is also some evidence that air pollution mainly affects children through respiratory illness, whereas the elderly are affected more through cardiac illness (Barnett et al., 2005; 2006).

Health effects that result from elevated levels of particulate matter (PM) in the air may be as minor as irritations to the nose and throat. However, pre-existing cardiovascular and respiratory diseases can become aggravated as air quality decreases, leading to social costs such as increased hospital admissions, physician visits, absences from school, and in the worst case, premature death (Otago Regional Council, 2005).

In Christchurch, an increase of 10 $\mu g\ m^{-3}$ of PM10 on the day prior to death was associated with a 1% increase in all cause mortality, and a 4% increase in respiratory mortality (Hales et al., 2000), indicating that there is a lag effect between pollutants being released into the atmosphere, and the subsequent impacts on health. In Australia and New Zealand, PM has been responsible for statistically significant increases in hospital admissions for pneumonia, bronchitis and respiratory problems in children, and cardiac problems in the elderly (Barnett et al., 2005; 2006).

2.4 Scales

The concept of scales is important in understanding air pollution meteorology. In the atmosphere, the smallest scale is represented by tiny swirling eddies with a size range of 10 cm to 100 m, and a lifetime of only seconds. At the other end of the continuum are jet streams, which are thousands of kilometres long and circle the earth over a time frame of months (Oke, 1987). Macro-scale movement is mainly horizontal, whereas micro-scale movement is mainly vertical (Sturman & Tapper, 2006). Phenomena that lie between these two extremes are shown in Figure 2.2.

An example of a micro-scale process is the way in which wind flows around a building, whereas a meso-scale process is the way that the dominant wind flow interacts with the

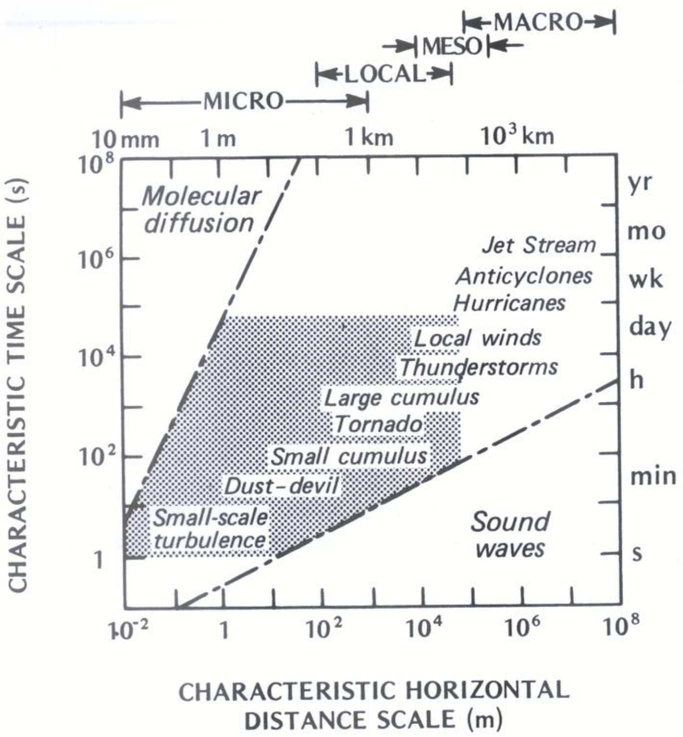

Figure 2.2 Time and space scales of a variety of atmospheric phenomena. Source: Oke, 1987, p4.

local topography, forming land-sea or mountain-valley breezes. A synoptic (macro) scale process refers to the passage of anticyclones, cyclones, and frontal systems. Scales from micro through to macro are important for air pollution processes; these are discussed in more detail below.

2.5 Components of Air Pollution

The amount of air pollution at any given site is determined by two main factors: the nature of the emissions, and the state of the atmosphere (Oke, 1987). A third factor is the interaction of meteorology with topography, which can produce localised thermal circulations. These three factors will now be described in detail.

2.5.1 Emissions

The release of emissions into the atmosphere, such as ash from a volcano, is a natural process. It is only when the level of emissions becomes too high that air quality is compromised. Nearly all atmospheric particulates come from natural sources such as volcanic eruptions, sea salts, smoke from forest fires, and mineral dust from deserts. However, these particulates are usually larger, so their effects on human health are minimal; the location of release may also be removed from any human habitation. Particulates of anthropogenic origin from combustion and industrial processing are smaller in diameter so have more potential to adversely affect human health. They are also released in the same location as people live (as opposed to a forest fire), and are released at a rate that elevates the process from a natural one to a potentially harmful one.

As well as the rate and the physical and chemical nature of the emissions, it is also important to know the shape of the emission area. For example, a point source may be represented by a chimney, a line source by a road, and an area source by a city. The duration of release, and the effective height of release (as this may determine how well the PM mixes in the atmosphere) are also important (Oke, 1987).

The size of the particulates is a determining factor in their dispersion and suspension lifetime. Particulates can range in size from 100 µm to less than 0.1 µm in diameter. However, those greater than 10 µm are usually in the form of dust, grit, and ash, and, because of their weight, tend to fall out of suspension fairly quickly and near their source by gravitational settling. Particulates less than 10 µm in diameter remain suspended for longer, and hence are more heavily influenced by meteorological variables (Oke, 1987). As discussed in Section 2.3, it is these particles that impact negatively on human health.

2.5.2 State of the Atmosphere

Once emissions are released, the state of the atmosphere determines their movement. This can vary greatly, from effective dispersion in an unstable atmosphere resulting in little impact on human health, through to poor dispersion and major health impacts. The atmospheric variables that control dispersion efficiency will now be described.

Atmospheric Stability

One of the most important meteorological controls on the dispersion of PM is atmospheric stability, which is determined by the temperature profile of the lower atmosphere (troposphere). The temperature of the troposphere is normally greatest at the Earth’s surface, where shortwave radiation from the sun is received and longwave

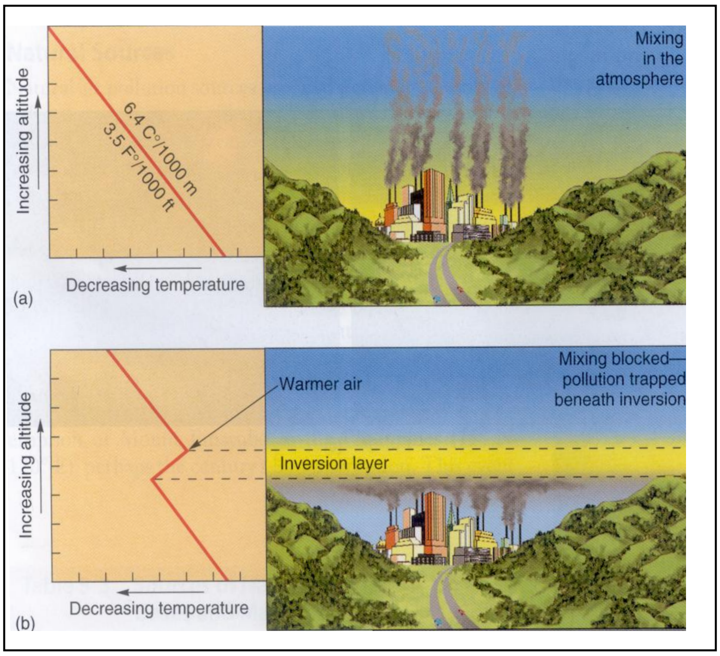

Figure 2.3 A lapse profile (a) shows temperature decreasing with height which allows dispersion of pollutants through convective mixing. When temperature increases with height (b) pollutants become trapped near the surface. Source: Christopherson, 2000, p74.

radiation from the earth is emitted. Temperature then decreases with height, which causes convective mixing. This is known as a normal, or lapse, profile (Figure 2.3a). However, under some conditions, temperature can increase with height, which causes atmospheric stability as mixing is inhibited. This is known as a stable, or inverted, profile and is shown in Figure 2.3b.

On a small scale, atmospheric stability changes can occur with the passage of weather fronts. For example, warm air behind a warm front will replace cool air by advection from aloft as the front passes over. However, because weather fronts are moving, their influence on atmospheric stability is usually short lived; hence their impact on air pollution is minimal (Oke, 1987).

At a larger scale, a stable atmosphere can be created under anticyclonic conditions. The descending air of the high pressure system compresses and warms at a rate of approximately 10 °C per kilometre (Oke, 1987) as the surrounding air pressure becomes greater. The descending air acts as a lid by trapping a layer of the cooler air beneath it, which strongly inhibits any vertical mixing; a situation that is made worse

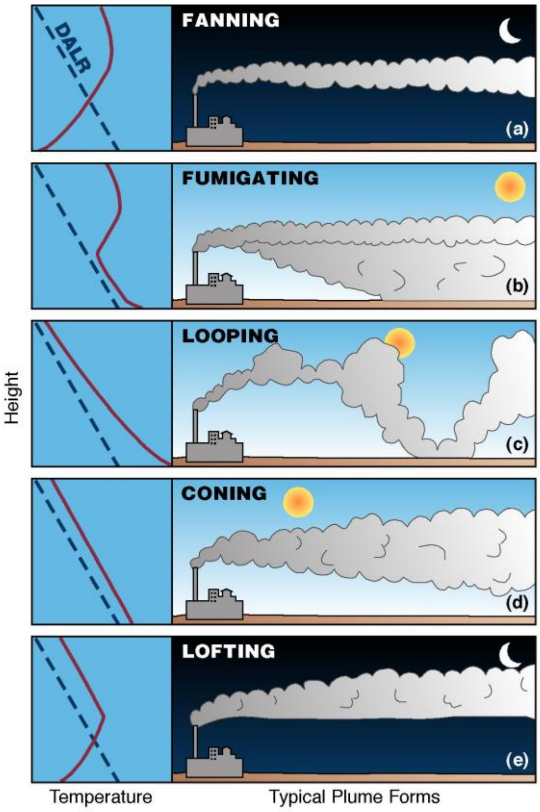

Figure 2.4 The daily cycle of dispersion of atmospheric pollutants in relation to atmospheric stability. Fanning (a) shows little mixing due to the presence of a ground-based radiation inversion. Fumigation (b) shows transport of pollutants from aloft to the surface due to the combination of surface heating and the presence of an elevated temperature inversion. Looping and coning (c and d) show better mixing due to an unstable atmospheric profile, and lofting (e) shows upward mixing only due to the formation of a radiation inversion at the surface but an unstable layer still remaining above. Source: Whiteman (adapted from), 2000, p217.

by the fact that high pressure systems are usually associated with little or no wind. This situation is known as an ‘elevated inversion’ (Figure 2.3b) and can persist for several days. It is a particular problem in winter, when surface-based radiation inversions also occur.

Radiation or surface-based inversions usually occur on nights with little or no cloud and little or no wind. Long wave radiation is released from the earth’s surface which causes it to cool, and the air aloft to then be warmer. This type of inversion is based at the ground and can extend 50-100 m above ground level. The earth releases longwave radiation continuously, but it causes cooling only when shortwave radiation stops being received (when the sun goes down). Consequently, a radiation inversion may be at its

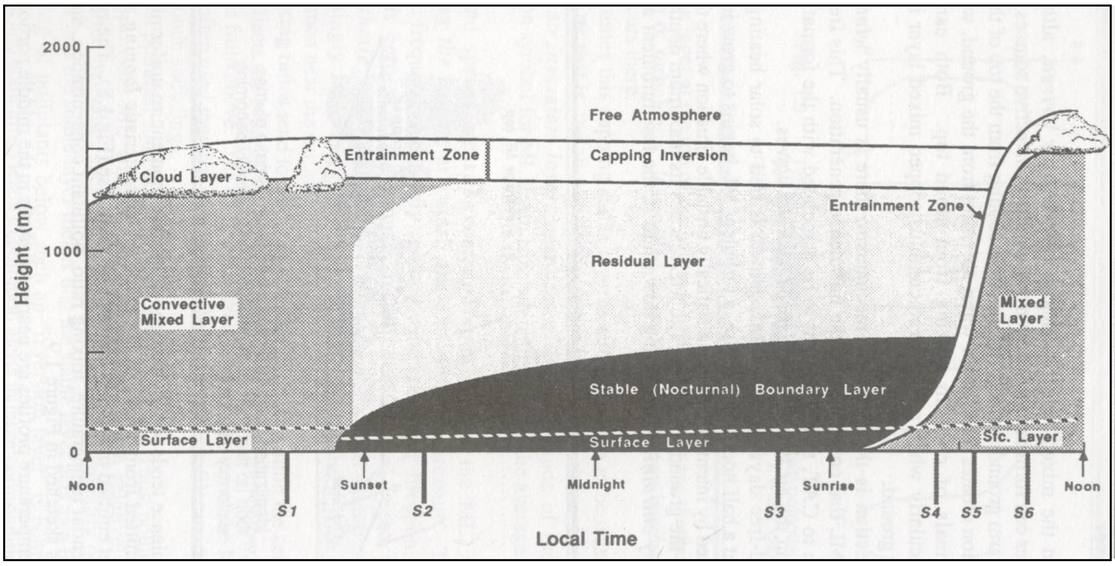

Figure 2.5 The daily cycle of boundary layer growth and erosion under anticyclonic conditions. Convective mixing occurs during the daytime due to a normal atmospheric temperature profile, but is suppressed during the night-time due to a stable atmospheric temperature profile. Source: Stull, 1998, p11.

strongest just before the sun comes up, as radiative cooling has been occurring throughout the night.

The nature of dispersion of the pollutants as they are transported away from their source is closely related to atmospheric stability (Figure 2.4). This in turn tends to follow a daily cycle of boundary layer growth and erosion (Figure 2.5). During the daytime, surface heating creates a convective mixed layer (S1 in Figure 2.5) and pollutants are dispersed effectively (Figure 2.4c). After sunset however, convective mixing ceases and a stable boundary layer develops (S2 in Figure 2.5). This results in poor dispersion of pollutants as shown in Figure 2.4a and e. After sunrise, convective mixing is established again (S4 in Figure 2.5), but this can also be a dangerous time of day for air pollution because surface heating will erode the inversion from below but a stable layer still remains aloft. The pollutants at the top of the unstable layer will then be transported down to the earth's surface in a process known as fumigation (Figure 2.4b).

Wind Speed and Direction

The three main forces influencing the generation of wind are the Earth's rotation, pressure gradients, and friction. Pressure gradients are caused by uneven distribution of atmospheric mass, but are counteracted by gravity, resulting in greater horizontal movement than vertical. The pressure gradient force and the Coriolis force both act to bend winds so that they blow parallel to isobars. This is of less importance at local scales however, where winds respond more to synoptic and surface induced effects and the movement of air masses occurs in more equal measures horizontally and vertically, often resulting in complex wind regimes (Sturman & Tapper, 2006).

Wind speed is important in controlling air pollution because it transports emissions away from their source. High wind speeds effectively reduce air pollution through forced convection and turbulence. However, in some cases, wind speeds above a certain threshold can worsen air pollution by causing particles on the ground to become entrained (Hien et al., 2002). Similarly, wind direction is important in determining where emissions are received. Depending on wind direction, a given site can receive large amounts of air pollution or none at all (Oke, 1987).

Humidity

The amount of water vapour in the atmosphere also affects air pollution. Particulates can adsorb to water droplets in the atmosphere through hygroscopic growth. Several particulates may adsorb onto one water droplet which will increase its mass and weight, causing it to fall out of suspension. This process is amplified during precipitation events which have a cleansing effect on the atmosphere. Conversely, the absence of moisture can prolong the residence time of PM in the atmosphere, as the PM's small size and light weight allows it to remain suspended for longer.

2.5.3 Thermal Circulations

Thermal circulations occur at the meso-scale and local scale. They are the result of synoptic scale circulations interacting with the local topography, which creates smaller scale thermal and dynamic effects (Sturman, 2001). The different types of thermal circulations will now be explained.

Slope Winds and Mountain-Valley Winds

Slope winds are driven by temperature differences between air over a slope and air at the same elevation over the centre of the associated valley (Whiteman, 2000). During the day, solar radiation heats a slope which in turn heats the air above the slope, causing

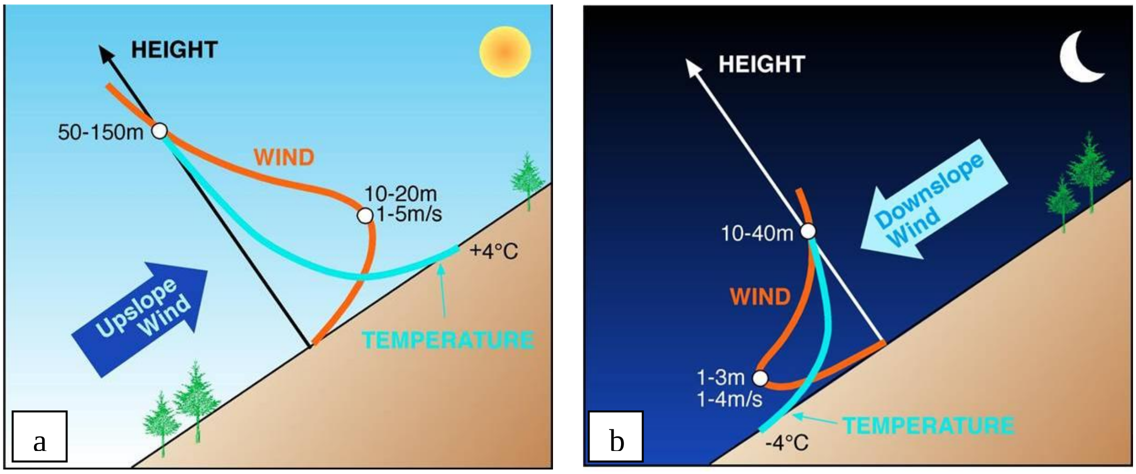

Figure 2.6 Slope winds. Daytime surface heating of a slope causes warmed air to rise and cooler air to be drawn up from lower elevations as an up-slope wind (a). After sunset the slope and surrounding air cool quickly, the cooler air is drawn back to lower elevations as a down-slope wind (b). Source: Whiteman, 2000, p187.

it to be warmer than the air further away. The warmer air then moves up the slope, drawing cooler air up from lower elevations (Figure 2.6a); these flows are known as up-slope or anabatic winds. The warm air is then drawn back towards to middle of the valley, and once it cools it descends again, forming a closed circulation (Whiteman, 2000). After sunset the slope cools quickly, which in turn cools the air above the slope, causing it to be cooler than the air further away. The now cooler air descends back down the slope as a down-slope or katabatic wind; a complete reversal of earlier in the day (Figure 2.6b).

Mountain-valley winds operate through a similar process to slope winds, but at a larger scale. The pressure differences that occur in complex terrain as a result of horizontal temperature differences generate winds that blow from areas of lower temperatures and higher pressures to areas of higher temperatures and lower pressures. As with slope winds, the circulation is closed by a reversal of these winds at higher levels in the atmosphere (Whiteman, 2000). During the day, surface heating generates winds that flow in up-valley direction; this is the valley wind (Figure 2.7a). This airflow reverses at night, becoming a mountain wind (Figure 2.7b).

Aspect is also important in the formation of mountain-valley winds, as slopes that are perpendicular to the sun will heat faster. For example, in the Southern Hemisphere, a valley with an east-west orientation will receive more radiation on its northern facing

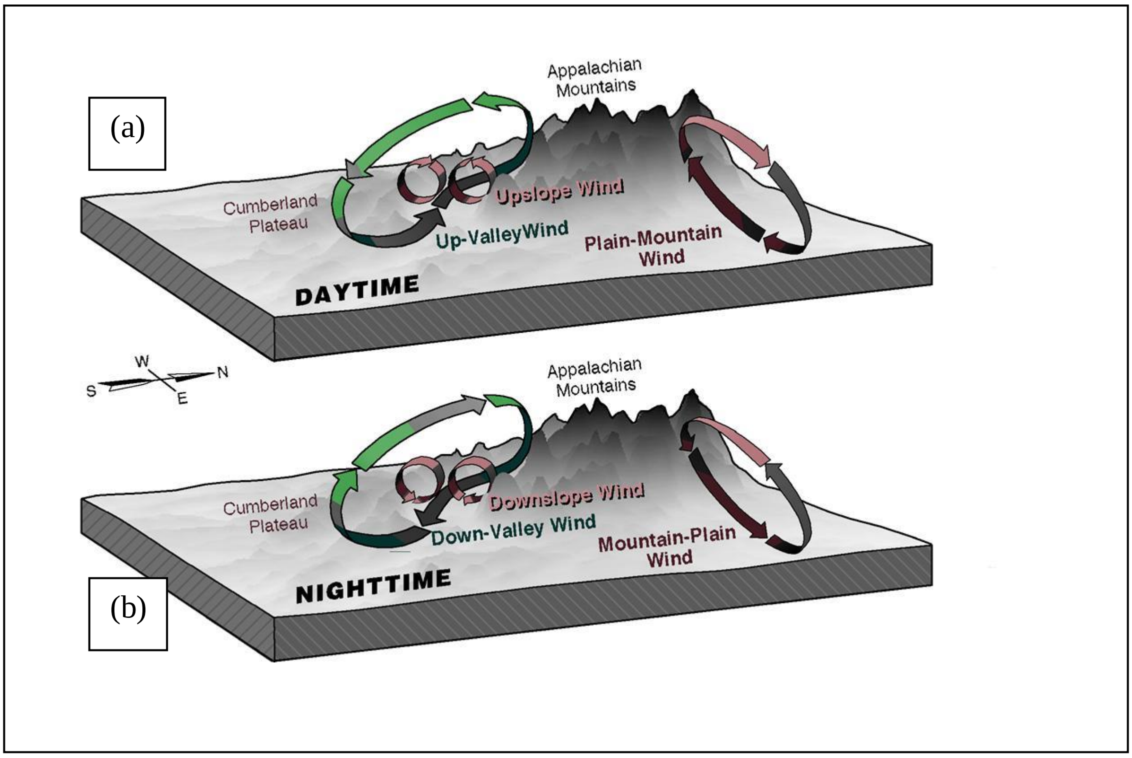

Figure 2.7 Mountain-valley winds. Surface heating causes air to be drawn up-valley during the day (a), and enhanced surface cooling at higher elevations causes air to be drawn back down-valley at night (b). Source: Whiteman, 2000, p172.

slopes than its southern facing ones, thus creating an across valley circulation as well (Sturman, 2001).

Slope and mountain-valley winds are potentially problematic for the dispersion of air pollution, especially if the emission source is located at the bottom of the valley. This is because down-slope and mountain winds will cause cold air to drain to the lowest elevations, creating a stable atmosphere which will inhibit dispersion. Also, if the emission source is located on the slope, the emissions will be transported downhill from there, thus increasing concentrations at lower elevations.

Basin Winds

Diurnal heating and cooling cause slope winds in basins, however, these winds are usually light due to the absence of mountain-valley winds. The topography surrounding basins also protects them from synoptic winds. The formation of nocturnal temperature inversions is common in basins, as cold air drains off the basin sidewalls and forms a cold air pool over the basin floor. In summer, the inversion is broken up daily through convection; however, in winter surface heating may be insufficient for breaking up the inversion, which can allow it to persist for days (Whiteman, 2000). This poses a problem for air pollution concentrations, which will build up in the cold air layer.

City-Country Breezes

Due to their highly modified nature, urban areas can display thermal, geometrical, and moisture characteristics that are significantly different from rural areas. The lower albedo of surface materials such as concrete and tar absorb and store heat during the day, which is then released slowly at night. The nature of the surface geometry of buildings also slows radiative loss at night. Furthermore, artificial heat is emitted from vehicles and industrial activity. All this, coupled with less evapotranspiration due to a reduced amount of water and vegetation may result in an atmosphere that is both warmer and drier than the surrounding atmosphere (Sturman & Tapper, 2006).

Under calm synoptic conditions, the warm polluted air above the urban area rises, which allows cool clean air from the surrounding rural areas to be drawn in. As the urban air cools, it descends, creating a thermal circulation in which polluted air is transported from the city to the country, and clean air is transported from the country to the city; this is called a city-country breeze. Having discussed the processes important in air pollution meteorology, the next section considers the meteorological context for air pollution in New Zealand.

2.6 The Meteorological Context for Air Pollution in New Zealand

Synoptic scale patterns in atmospheric circulation are the main influence on New Zealand’s weather. At the synoptic scale, both horizontal and vertical movement of air masses take place over a distance of thousands of kilometres and a time frame of approximately one week (NIWA, 2001). Being in the mid latitudes of the Southern Hemisphere, New Zealand is in the zone of the westerlies. The mid latitudes experience a steep latitudinal thermal gradient, so thermal wind is a strong component of the weather (Sturman & Tapper, 2006). The expanse of water that surrounds the country also affects New Zealand’s weather. The oceans moderate the effect of the synoptic weather systems by acting as a buffer, which results in a temperate climate that is neither extremely hot nor extremely cold (Sturman, 2001). This is particularly true at coastal areas but applies less to inland areas, which have a more continental climate with a greater annual temperature range.

The dominant westerly winds are created by the interaction of the Southern Ocean lows to the south and the subtropical highs to the north. The convergence of the polar and subtropical air masses causes many frontal systems, which are the result of transient eddies coming from the mid tropospheric waves (Sturman & Tapper, 2006). The Southern Ocean lows tend to pass quickly from west to east, and below New Zealand, but affect the weather by extending troughs over the country. They usually bring a southerly change, especially for the South Island, and are mature by the time they arrive, having originated thousands of kilometres to the west (Sturman, 2001).

Tasman Sea lows are also an important feature of New Zealand's weather. These have the potential to develop rapidly over the Tasman Sea where less data is available, making them more difficult to forecast. They tend to move more slowly and erratically, and the weather they produce can vary depending on which part of the country they affect (Sturman, 2001). However, because they typically involve higher wind speeds and precipitation, these conditions are conducive to dispersion and therefore are not precursors for air pollution episodes.

Further north are the subtropical highs, which are generated by the descending limb of the Hadley Cell. They move more slowly than the Southern Ocean lows and can stagnate over the country causing anticyclonic blocking (Sturman, 2001). These conditions provide ideal precursors for air pollution episodes. In spring (September - November) the dominant westerly airflow becomes more persistent (Sturman, 2001), producing erratic, changeable weather. Then, in summer (December- February) the subtropical highs migrate south and increase in frequency, which also pushes the westerlies and the Southern Ocean lows further south (NIWA, 2001). Autumn tends to bring settled weather to the entire country, and then in winter, as the subtropical highs move back to the north, the low pressure systems become more dominant over the country, although anticyclonic blocking can still occur. It is the presence of anticyclones during the winter months that often compromises air quality.

The synoptic circulation pattern over New Zealand seems to follow a seven day cycle in which highs and lows alternate as one replaces the other. However, this pattern is frequently disturbed by phases of zonal or meridional flow, and by changes in the Southern Oscillation between El Niño and La Niña (Sturman, 2001).

2.7 Air Pollution in the South Island

Christchurch, the South Island's largest city, has a long standing air pollution problem, the processes of which have been well studied. Most other New Zealand towns and cities that suffer from air pollution share a similar set of factors that, when combined, result in levels of PM10 air pollution that often breach the National Environmental Standard (NES) of 50 µg m^{-3}.

The local topography is an important contributing factor for urban areas with air pollution problems. Many South Island towns that suffer from air pollution are either partially or fully surrounded by hills (however, this is not a necessary requirement, as towns that are not enclosed by hills, such as Oamaru, can also have air pollution problems). This inhibits ventilation and encourages nocturnal drainage winds which cause colder air from the elevated hill slopes to sink and pool at the bottom of the valley or basin, which is often where the towns are located. If the hill slopes are populated, these drainage flows will also carry particulates to lower elevations. In all cases air pollution is mainly a problem in the colder months, when emissions from domestic heating are added to the more constant levels of emissions from vehicles and industry, at a time of increased atmospheric stability.

Under anticyclonic conditions, nocturnal radiation inversions are common during winter in New Zealand, and particularly in the South Island. They build up after sunset and persist through the night in the absence of cloud and wind. The descending air of the anticyclonic weather system coupled with the nocturnal drainage winds generates a stable atmospheric profile, which can trap pollutants near the surface. The associated cold temperatures leads to more use of domestic heating appliances, further exacerbating the problem.

Alexandra, Central Otago and Mosgiel, in eastern, coastal Otago are two South Island towns that suffer from air pollution problems during the winter months, with breaches occurring each winter. Because of this, constant monitoring of PM10 and meteorological variables are carried out by the Otago Regional Council. A summary of the research conducted to date is presented below.

2.7.1 Alexandra

The Central Otago town of Alexandra has experienced some of the highest levels of PM10 in the Otago region, with daily averages reaching as high as 150 µg m^{-3}. Between 1999 and 2009 Alexandra has averaged 41 breaches of the NES per year. Because 99% of Alexandra's emissions are from domestic sources (Wilton, 2006), PM10 levels are only a problem during the winter months (which is considered to be from May to August in southern New Zealand) when domestic heating appliances are used and atmospheric stability is greatest. Outside of the winter months air quality in Alexandra is good, with daily PM10 levels mostly below 20 µg m^{-3}.

Despite Alexandra's long-standing air pollution problem, limited research on the air pollution meteorology of the town has been carried out. Tate and Spronken-Smith (2008) determined that a high air pollution day can be predicted by sub-zero temperatures and wind speeds below 0.5 m s^{-1} at either 0800 or 0900 hours that day, with the use of these criteria correctly predicting 60 % of high pollution days. However, various scales of drainage flows and the occurrence of hoar frosts were found to be complicating factors. It was also suggested that cold air pooling in the Alexandra basin may facilitate decoupling of the atmosphere in the basin from that aloft, which would allow high pollution events to occur in a variety of synoptic conditions.

Research conducted by West (2008) has also provided some insight into the spatial variability of PM10 in Alexandra by way of mobile traverses using a DustTrak sampler mounted on a vehicle. The spatial distribution of PM10 showed pronounced variation between days sampled, but when all days were averaged the highest concentrations occurred in the centre of the town, which is also at the lowest elevation. This supports the theory of transportation of pollutants through drainage flows. West (2008) and the Otago Regional Council (2009a) also found that temperature inversions were occurring

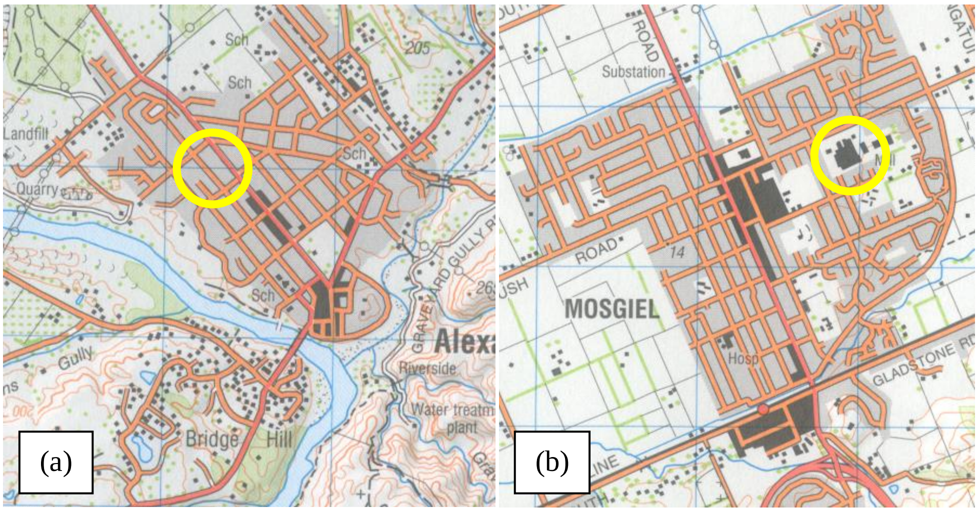

Figure 2.8 Topographical maps of Alexandra (a) and Mosgiel (b), scale: 1:50 000. The locations of the ORC monitoring sites are shown by the yellow circles.

in Alexandra through the installation of five temperature sensors at increasing elevations on Bridge Hill to the south of the town (Figure 2.8a). Under stable atmospheric conditions, the temperature at the top of the hill was approximately 2 °C warmer than at the monitoring site in the town. This research has provided valuable information on the air pollution meteorology of Alexandra; however, there is still a paucity of knowledge regarding the intricacies of the processes in operation here. In particular, there is limited knowledge of the spatial patterns in air pollution meteorology, both horizontally and vertically.

2.7.2 Mosgiel

Mosgiel has averaged 10 breaches of the NES per year between 2001 and 2009. As with Alexandra, high pollution events are confined to the winter months with daily average values occasionally reaching 100 µg m^{-3}, but more commonly falling between 50 and 100 µg m^{-3}. Domestic emissions contribute 90% of air pollution in Mosgiel, with industry contributing the remaining 10% (Wilton, 2006). Daily air pollution levels outside of the winter months are mostly below 20 µg m^{-3}. Interestingly, during the winter months, the main peak in PM10 levels in Mosgiel occurs in the morning between 0900 and 1000 hours, with a smaller peak in the evening (Otago Regional Council, 2009a).

As with Alexandra, limited air pollution research has been carried out in Mosgiel. However, Mulliner et al. (2007) found that minimum air temperature and low wind speeds were correlated with an increase in PM10, and the occurrence of rainfall was correlated with a decrease in PM10. These correlations were statistically significant at the 99% confidence interval, but were not strong.

Mobile traverses using a DustTrak were also carried out in Mosgiel in the winter of 2008 by both the Otago Regional Council and the University of Otago. It was found that there was significant variability in PM10 levels across the town but there was a tendency for the northern and western parts of the town to have the highest readings, with central and eastern areas having more moderate readings. Considering that on high pollution nights light winds occurred from the north-east through to the south-east, it can be assumed that these winds are drainage flows from the surrounding hills which are transporting pollutants from east to west (Otago Regional Council, 2009b). This may also explain the lower evening peak in PM10 mentioned above. Under the calm settled conditions that are required for both drainage flows and elevated pollution levels to occur, the transportation of pollutants from east to west means that they are being transported away form the monitoring site which is situated in the north-east of the town (Figure 2.8b), and therefore not being effectively captured by the monitor. In this case, numerical modelling would be a valuable tool for simulating the wind regime, and shedding more light on the air pollution meteorology here.

Other air pollution research in the Otago region includes a study of the temporal variations of PM10 concentrations in South Dunedin using DustTrak sampling (Osman, 2007), a study of a high pollution event in Mosgiel using point source data and numerical modelling with TAPM (Reese, 2009), and a study of the air pollution meteorology in Milton using point source data and numerical modelling with TAPM (Broadbent, 2010).

2.8 Air Pollution Modelling

Measuring air pollution and meteorological variables can be time consuming and costly, and only provides limited data, with little or no spatial resolution, either horizontally or vertically. Air pollution modelling therefore, is a valuable tool for simulating atmospheric circulation and pollution dispersion processes, allowing for a better understanding of these processes in three dimensions. The accuracy of such models has increased over time, and advances in computing power over the past few decades have allowed a shift from the traditional Gaussian plume/puff models to prognostic meteorological and air pollution models such as The Air Pollution Model (TAPM), which can easily be run from a desktop PC (Hurley et al., 2008; Hirdman, 2006).

TAPM is a mesoscale prognostic numerical model that uses a series of one-way telescoping nested grids and consists of a meteorological component and an air pollution component. The meteorological component of TAPM is incompressible, non-hydrostatic, has a terrain-following coordinate system and solves primitive equations to produce three-dimensional simulations (Hurley, 2008a). Several verification studies have shown that TAPM is capable of predicting both meteorology and pollution concentrations in a variety of situations and locations (see Hurley et al., 2008). The properties of TAPM are explained in more detail in Chapter Three.

However, the complex topography of New Zealand, and particularly the Southern Alps of the South Island, poses a problem for terrain-following models such as TAPM, as they are not well suited to such environments (Zawar-Reza et al., 2005a). The complexity of the terrain in New Zealand results in equally complex meteorology such as terrain-induced drainage flows, cold air pooling, and temperature inversions, which adds another challenge to effective modelling (Gimson et al., 2007). This is further exacerbated by a lack of quality data which is needed to validate the model. Gimson et al. (2007) also suggest that the grid spacing of the innermost grid should not be less than 1 km, which may be a problem if small-scale processes are trying to be captured.

Air pollution modelling in New Zealand is generally used to simulate the dispersion of PM10 (Zawar-Reza et al., 2005a). As discussed above, PM10 air pollution events in New Zealand tend to occur in the winter months under calm anti-cyclonic weather conditions, which are often associated with nocturnal temperature inversions. In this situation, TAPM has a tendency to overestimate low wind speeds (Gimson et al., 2007; Zawar-Reza et al., 2003; Conway, 2009), thus not capturing the calm conditions required for a temperature inversion to develop. In a year-long simulation of PM10 dispersion in Christchurch, it was found that TAPM underestimated calm conditions 11% of the time, and produced weak westerly drainage winds instead. These westerly winds were occurring aloft, but had been grounded by TAPM. The Index of Agreement (IOA) was 0.66 for wind speed and 0.87 for air temperature for this study (see Section 3.6.3 for more details). Despite this, TAPM produced a reasonably accurate annual average PM10 value of 18 µg m^{-3}, slightly lower than the measured average of 22 µg m^{-3} (Zawar-Reza et al., 2005b). It is also important to note that the PM10 value produced by TAPM is for the volume of a grid, whereas the measured value is for a point only (Zawar-Reza et al., 2005c).

Conversely, a year long simulation of smog and particulate dispersion (both PM10 and PM2.5) in Melbourne, Australia found that TAPM replicated the meteorology well, with an IOA of 0.88 for wind and 0.95 for temperature without any data assimilation. Adding data assimilation improved the meteorology further, but the difference was small. Extreme high concentrations of smog (NO_2 and O_3) were predicted to within 9% and particulates to within 13% over one year from July 1997 to June 1998 (Hurley et al., 2003).

Similarly, TAPM was able to simulate meteorological and air pollution processes in Milton, Otago, for the winter of 2008, with an IOA of 0.77 for temperature and 0.58 for PM10 when data assimilation was included. PM10 concentrations tended to be under-predicted by TAPM, however, extreme pollution events were over-predicted (Broadbent, 2010).

Other studies of air pollution meteorology in South Island towns had limited success with TAPM. In Rangiora and Kaiapoi (two small towns just north of Christchurch) TAPM was used to investigate whether drainage flows were transporting pollutants from one town to the other. Hamilton et al. (2004) found that TAPM was able to simulate these drainage flows effectively, but no information on the meteorological component of TAPM was provided, or whether the modelled pollution levels were similar to those observed.

In Invercargill, Conway et al. (2007) also used TAPM to simulate the dispersion of PM10 across the city, but with limited success. TAPM was able to reproduce the larger scale drainage flows but not the local scale ones, and peak PM10 concentrations were also hugely overestimated.

The tendency for wind speeds to be overestimated during calm conditions is common among terrain-following mesoscale models (Gimson et al., 2007; Zawar-Reza et al., 2003). This may be due to the placement of the lateral boundaries of the grids. If the lateral boundary is over an area of steep or complex terrain, unrealistically high wind speeds may be produced and the calm conditions that are occurring will not be well captured. However, this problem may be overcome by either smoothing the topography or moving the lateral boundary of the grid slightly (Zawar-Reza et al., 2005c).

The overestimation of wind speed then leads to an overestimation in temperature. Gimson et al. (2007) found that for studies at Edendale and Tiwai Point (Southland, New Zealand), TAPM overestimated temperature for the winter months, but the modelled data was a better match with the observed data for the warmer months. The overestimation of wind speed and temperature were both occurring during the night and early morning, again indicating that the conditions necessary for a temperature inversion were not being well captured. This was also found by Zawar-Reza et al. (2003) for a study in Christchurch, and has implications for the air pollution modelling component of TAPM, as, under the modelled conditions, PM10 will be flushed out more quickly than in reality.

Under settled anti-cyclonic conditions, surface energetics are the main drivers of low level airflows. Therefore, comparing modelled and observed surface energy balances is an effective tool for model validation. For a study conducted in Christchurch, Zawar-Reza et al. (2005c) found that net all-wave radiation and latent heat fluxes were replicated well, but the sensible heat flux was overestimated. This was because TAPM adds an anthropogenic component of 30 W m^{-2}, however, for Christchurch, this value has been estimated at 6 W m^{-2}. Hirdman (2006) also found that increasing the deep soil volumetric moisture content in the model set-up helped to reduce the sensible heat flux. This is unlikely to be an issue for air pollution modelling in small towns however, where there will probably be no anthropogenic component.

2.9 Summary

Air pollution has always existed, and will continue to exist as a by-product of human activity. The health effects of exposure to air pollution have become increasingly well understood, as has our understanding and knowledge of how and why air pollution happens. Air pollution regulations have improved over time as a result. In New Zealand, and particularly in the South Island, breaches of the NES occur during the winter months in many towns, mostly from domestic sources. These breaches are usually associated with the interaction of anticyclonic weather patterns (which produce low temperatures and low wind speeds), and local scale processes such as cold air drainage and temperature inversions. Local topography is also an important factor, as the presence of hills around a town facilitates drainage flows and inhibits dispersion through sheltering. Both Alexandra and Mosgiel suffer from poor air quality from PM10 pollution in the winter months. Whilst there is good observational data from an Otago Regional Council monitoring site in each town, only a few attempts have been made to capture spatial patterns. Importantly, the potential of numerical modelling has yet to be explored in terms of whether it can further understanding of the air pollution meteorology in these contexts. The next chapter will describe the two towns of Alexandra and Mosgiel, as well as presenting the methods used for conducting this research.

3

Methods

3.1 Introduction

In this chapter, the physical setting of Alexandra and Mosgiel will be described. This will include the climate, topography, and land use of each town. The remainder of the chapter will describe the research methods. The site locations and instruments used to collect the existing PM10 and meteorological data will be described, and the data analyses conducted. The details of the different components of the model setup will also be provided, as well as the techniques used for model validation.

3.2 Physical Setting

3.2.1 Alexandra

Alexandra is at a latitude of 45 °S, a longitude of 169 °E and an elevation of 141 m above sea level. The town is situated at the confluence of the Clutha River and the smaller Manuherikia River in Central Otago (Figure 3.1). The Cairnmuir Mountains lie to the northwest and the Dunstan Mountains to the northeast, and these, as well as other hills to the south, encircle the town. Gently sloping land lies to the west and north of the town which is used mainly for farming and agriculture, and Clyde, Alexandra’s closest town, lies approximately 9 km to the northwest.

Since the town is located in an inland basin, the climate approaches continental-type conditions with dry warm summers and cool winters. The climate is highly influenced by the Southern Alps which, given predominately westerly airflow, results in a rain

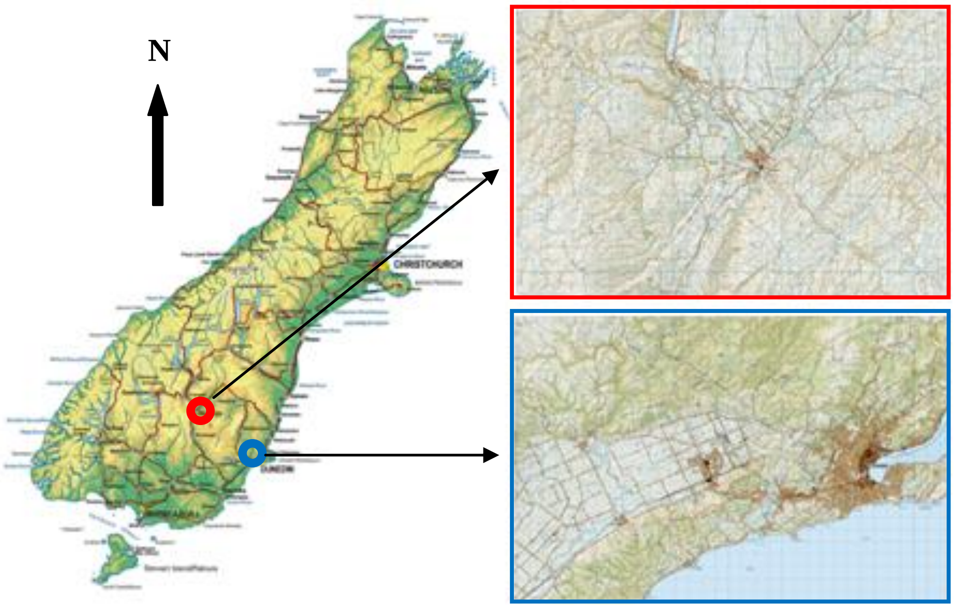

Figure 3.1 Map of the South Island showing the locations of Alexandra (red) and Mosgiel (blue).

shadow area over the eastern parts of Central Otago. Thus Alexandra's annual rainfall is only 358 mm and there are long periods without rain, particularly in summer. Summer daytime maximum temperatures range from 20-26 ºC, and can reach above 30 ºC. Winters are cold with frequent and often severe frosts and occasional snowfall. Winter daytime maximum temperatures range from 3-11 ºC (NIWA, 2010a).

Since Alexandra is located in a basin, during calm clear conditions in winter there is the generation of nocturnal cold air drainage, with cold air draining from the hill slopes into the basin. This can result in intense and persistent temperature inversions, which can last for several days. Despite the fact that the South Island generally receives more low pressure systems in winter, in Alexandra high pressure systems are more frequent (NIWA, 2001). Alexandra has a small population of only 4400, and the town is mostly composed of residential areas. Therefore, domestic emissions are the main contributor of pollutants, with industrial activity only responsible for approximately 1% of total emissions (Wilton, 2006).

3.2.2 Mosgiel

Mosgiel is at 45 °S and 170 °E, but has a much lower elevation of only 20 m above sea level. The town is situated at the north-eastern end of the Taieri Plains, a fertile area used for agriculture and dairy farming, and the Silver Stream (a tributary of the Taieri River) runs along the town's northern boundary. The climate of Coastal Otago is characterised by cool coastal breezes, and exposure to the unsettled weather from the south and southwest. North-westerly conditions sometimes lead to high temperatures in summer, with average summer temperatures ranging between 16 and 23 ºC, and occasionally rise above 30 ºC. Winters are cold with occasional snowfall and frequent frost, and average winter maximum temperatures range from 8-12 ºC (NIWA, 2010b). Mosgiel receives approximately 750 mm of rainfall per year.

Although Mosgiel is in close proximity to the coast, the sheltering effect of the hills that surround it on three sides results in a more continental type climate similar to that of other Central Otago towns such as Alexandra. It is not unusual for air temperatures in Mosgiel to be both hotter in summer and cooler in winter than nearby Dunedin. Mosgiel is technically a suburb of Dunedin City but lies 12 km to the southwest and inland and has a population of 9500. The town is bounded by the Chain Hills to the east, which separate it from Dunedin, and by the Silver Peaks to the north and west as well. The hills surrounding the town result in nocturnal drainage flows during the winter months, which inhibit the dispersion of pollutants (Mulliner et al., 2007). Domestic emissions account for about 90% of PM10 in Mosgiel, with the remaining 10% coming from industrial activity (Wilton, 2006). The majority of industrial emissions come from the New Zealand Wood Moulding Company which runs a wood waste fuelled boiler (Otago Regional Council, 2009a).

3.3 Overview of Research Methods

This research was aimed at gaining a better understanding of the air pollution meteorology in Alexandra and Mosgiel. Previous research and existing observational data provided the platform from which the numerical modelling employed in this research was built on. For this to be achieved, it was desirable to observe trends in air pollution over a number of years, rather than one winter alone. Therefore, existing data have been used, which provide information on the number of air pollution breaches that have occurred since 1999 in Alexandra, and since 2001 in Mosgiel. Air pollution monitoring in each town was sporadic until 2005, when continuous monitoring began. For this research, it was decided that three years of hourly data would be sufficient for revealing general trends at daily and monthly timescales. Therefore, the last three years (2007 – 2009) were selected for analysis. These existing datasets have been collected by the Otago Regional Council (ORC), with some additional data from NIWA's online climate database and an automatic weather station (AWS) dataset from West (2008). To address the second aim of this research, TAPM was used to simulate the wind and temperature regime in each town, as well as PM10 concentrations, over the course of an entire winter. First the output from TAPM was tested against the ORC observational data, then, secondly, TAPM was used to provide a detailed analysis of processes occurring at a diurnal scale, through a series of case studies.

Numerical models such as TAPM that describe liquid flow by solving primitive equations are more detailed and more comprehensive than the traditional Gaussion models which were more focussed on near-source maximum concentrations (Zawar-Reza et al., 2005a). The numerical model used for this research needed to be capable of simulating both meteorology and air pollution. TAPM filled these requirements and also had the added benefit of being able to be run from a desktop PC.

3.4 Observational Methods

3.4.1 Observational Data

Because breaches of the NES occur in both Alexandra and Mosgiel, the Otago Regional Council is responsible for continuous monitoring of air pollution levels in these two towns. In Alexandra, the monitoring site is at 65 Ventry Street (45° 15' S, 169° 23' E), while in Mosgiel, the monitoring site is on Factory Road (45° 53' S, 170° 20' E) (Figure 3.2).

As well as PM10, meteorological variables of temperature, wind speed, and wind direction are also collected by the ORC at hourly averages. PM10 data are recorded using a Beta Attenuation Monitor (BAM) made by Met One. The BAM works by continuously pulling a set amount of air through an intake tube at a height of approximately 4 m above ground level onto a filter tape; PM greater than 10 µm in diameter is removed by gravitational settling, so that only PM10 is collected. The amount of PM10 on the filter tape (Figure 3.3) is established by using high-energy

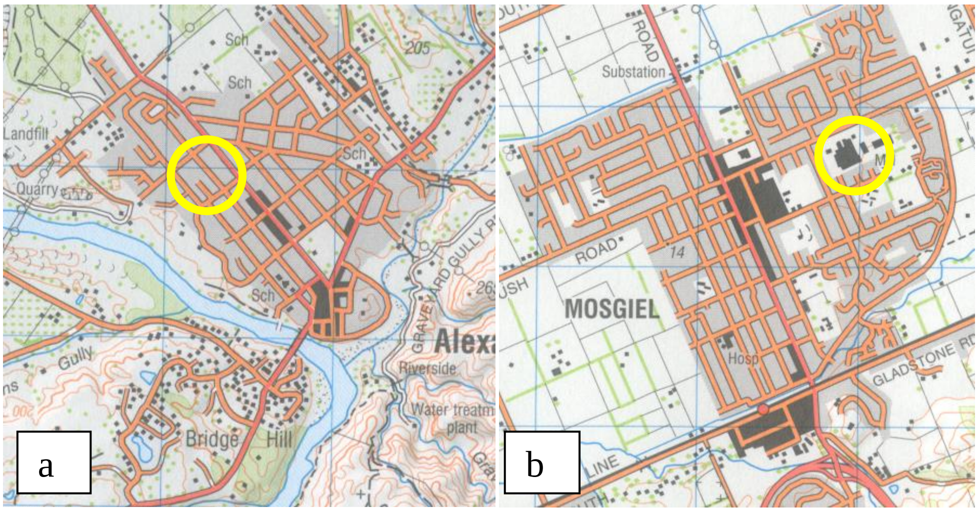

Figure 3.2 Locations of the monitoring sites for Alexandra (a) and Mosgiel (b). Scale: 1:50 000.

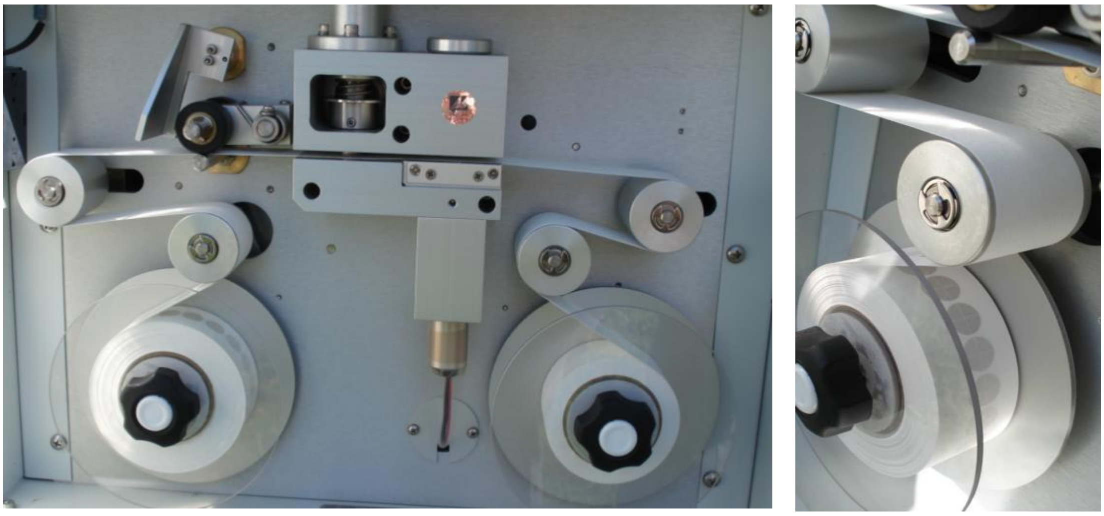

Figure 3.3 View of the filter tape inside the BAM. The reel of filter tape moves from right to left; the darkened circles show the PM10 collected each hour.

electrons (beta particles) which are emitted by a small element and detected by a scintillation counter on the other side of the filter tape. Attenuation of the beta-particle signal is measured on the clean filter tape first, which is then placed under the air intake tube for 50 minutes of each hour (the remaining 10 minutes used to conduct the calculation and prepare the next section of tape is included in the calculation, giving an hourly averaged value). The section of tape is then measured again and the difference in the degree of attenuation of the beta-particle signal can then be used to determine the mass concentration of PM10 on the filter tape, and thus, the mass concentration of PM10 in the atmosphere (BAM 1020 Particulate Monitor Operation Manual, 2001). The PM10 data, as well as being collected on a data logger within the BAM, are

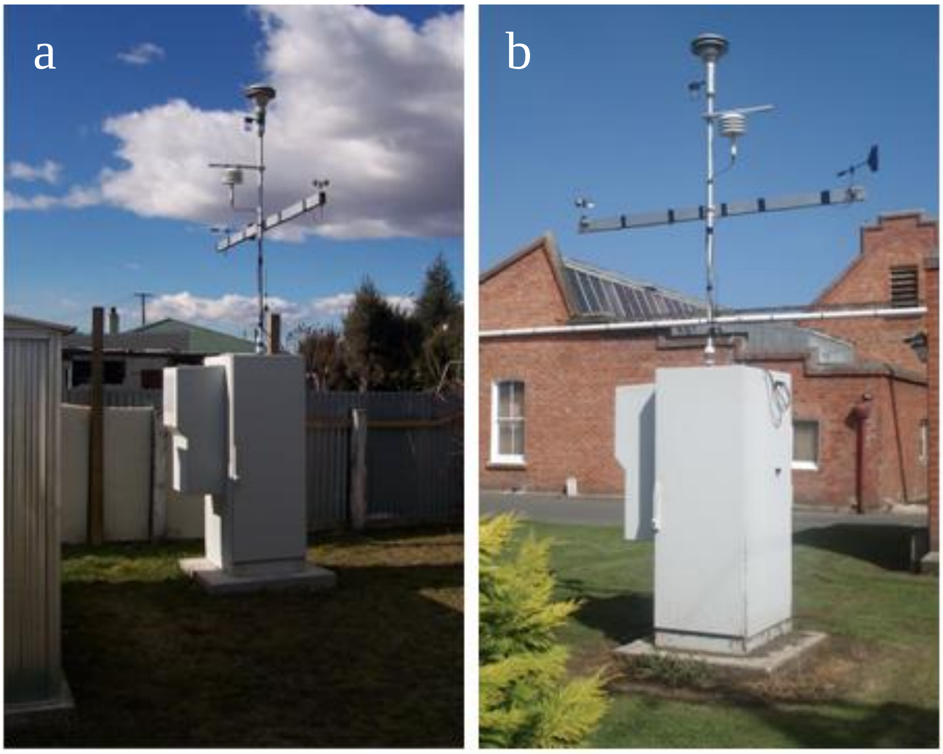

Figure 3.4 The Alexandra monitoring site (a) and the Mosgiel monitoring site (b). The air intake for the BAM is at the highest point and the temperature sensor, wind vane and anemometer are below.

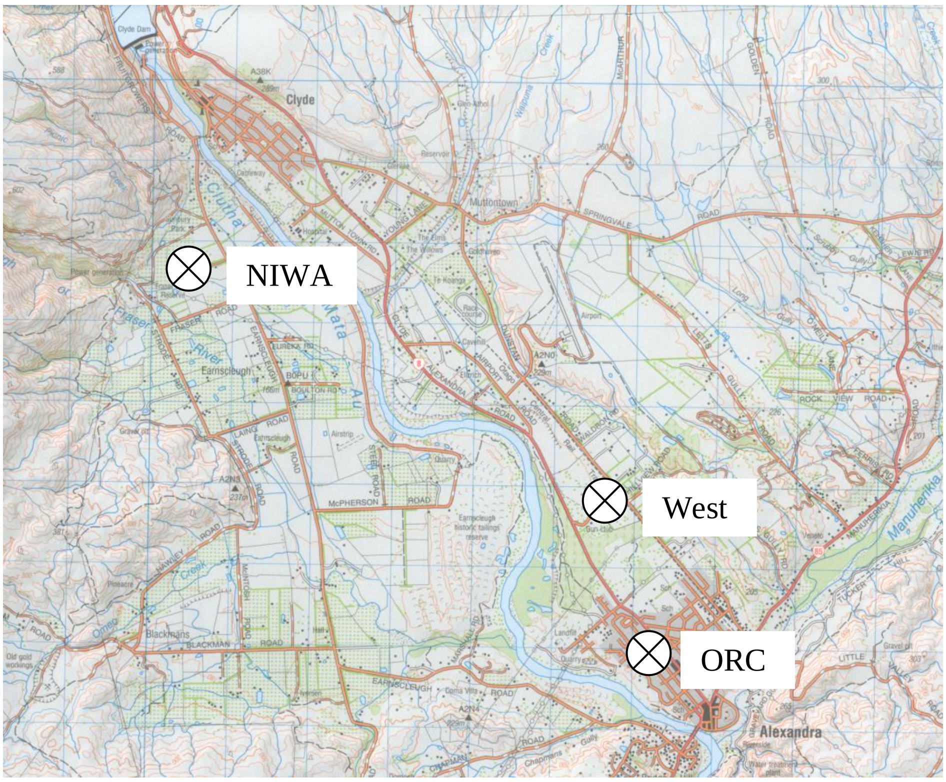

Figure 3.5 Locations of the three sites from which meteorological data were obtained for Alexandra.

instantly available at the ORC so that any malfunction in the instruments can be detected quickly.

Wind speed and direction data were recorded using a Weather Pro anemometer and wind vane, and temperature data were collected using a Met One temperature sensor. The temperature sensor, anemometer and wind vane are mounted on the BAM itself (Figure 3.4). The set-up and instruments are the same for both Alexandra and Mosgiel. The height of the anemometer and wind vane is approximately 3 m above ground level, which is less than ideal as, in order to collect accurate data, anemometers and wind vanes should be at a height of 10 m above ground level. Isolated objects such as trees should also be ten times their height away from the instruments (Manuell, 2001). The location of the BAM should also be situated in a part of the town where air pollution concentrations are greatest. Both monitoring sites are in reasonably close proximity to buildings which may affect wind speed and direction values, especially when these values are low.

To supplement the ORC data, additional meteorological data were also obtained for Alexandra. The first of these is a three month dataset from June to August 2008 collected by Owen West, a Masters student at the University of Otago in 2008. This monitoring site was located on a golf course two kilometres to the north-west of Alexandra (Figure 3.5). Temperature was recorded using a Skye probe, and wind speed and direction were recorded using a Porton wind vane and anemometer at 2.5 m above ground level. Although the height of the wind instruments is still lower than 10 m at this site, they are not shielded by any buildings; therefore these data are likely to be more accurate than the ORC data at Ventry Street. The second set of meteorological data were downloaded from NIWA's National Climate Database (CliFlo) from 2007 - 2009. Wind speed was measured with a Vector A101M anemometer, and wind direction with a Vector W200P potentiometer. The height of the wind instruments at this site is 10 m above ground level, but the site is approximately six kilometres to the north-west of Alexandra (Figure 3.5), so some variation in the wind regime is likely.

3.4.2 Observational Data Analyses

The raw data collected by the ORC are routinely quality controlled. In some instances, periods of several hours or in some cases several days are missing, but overall the dataset is complete and of good quality except for the issue of the height of the wind instruments mentioned earlier. PM10, temperature, and wind speed data were converted from hourly averages into daily averages and then daily PM10 data were plotted as a time series. Monthly ensembles were created for temperature, wind speed and PM10 to show seasonal trends, as well as scatterplots to show the strength of the relationship between the three variables. Rather than average wind direction data (which would hide the dominant wind regime) these data were plotted as wind roses. Diurnal ensembles of the high pollution days were also created for each town in order to reveal the temporal distribution of PM10 concentrations. Characterising the trends in air pollution over the previous three years showed which period of time within the dataset would be most useful to model. The model description, set-up and validation are presented in the following section.

3.5 Modelling Methods

3.5.1 Model Description

TAPM is a mesoscale prognostic numerical model that uses a series of one-way telescoping nested grids and consists of a meteorological component and an air pollution component. The meteorological component of TAPM is incompressible, non-hydrostatic, has a terrain-following coordinate system and solves primitive equations to produce three-dimensional simulations (Hurley, 2008a). Data is fed from the coarser resolution grids into the finer resolution grids with the number of grid points (x and y) defined by the user. The vertical levels (z) are defined by TAPM so that the lower levels are of a higher resolution than the upper levels, as these are of more importance to boundary layer processes.

For best results, the maximum area of the outside grid should be less than 1500 km by 1500 km as TAPM does not take into account the curvature of the earth. This means that deep atmospheric circulations or extreme weather events cannot be well captured, especially considering the incompressibility of the model. Also, because of the terrain following coordinate system, TAPM cannot be used for areas of very steep terrain such as cliffs or bluffs, as discontinuities in terrain height cannot be represented (Hurley 2008b).

The pollution module of TAPM calculates pollution concentrations for each grid cell; the size and resolution of this grid is also defined by the user. Emissions can be in the form of a point, line, area or building. For point sources, the height, emission rate, source radius, exit velocity and exit temperature must be defined, and for an area source the size and emission rate must be defined. Once the model has been run, data can be extracted from any grid point. The PC based graphical user interface (GUI) is designed to be used in conjunction with the Windows operating system through which it connects to a variety of databases such as terrain, soil type and synoptic scale meteorological analyses (Hurley, 2008a). Inputs are selected and outputs are viewed and analysed through this interface, with the option to export outputs to other software packages such as Excel. TAPM can be used to model meteorology in areas where no measured data exist; however, wind speed and direction data can be assimilated into the model to nudge modelled values towards measured ones (Luhar & Hurley, 2003).

3.5.2 Model Set-up

Meteorological Module Set-up

For Alexandra, the grid centre was located at 45º 15’ South and 169º 22.5’ East, which represents the southwest boundary of the town. For Mosgiel, the grid centre was at 45º 53’ South and 170º 20’ East, again representing the southwestern boundary of this town. In order to determine the parameters that would provide the best accuracy for both meteorology and pollution, a series of sensitivity analyses were conducted. This was done for Alexandra first, using one month of hourly data for May 2008, with the optimal settings for this town giving a good result for Mosgiel as well.

Three grids were used in the first four runs, with a grid resolution of 35 x 35 grid points. The nesting ratios were not changed from the default, with the grid spacing of the outermost grid set at 30 km, followed by 10 km for the second grid, and 3 km for the third grid. The first sensitivity analysis was run without the assimilation of wind speed and direction data. However, because of the model’s tendency to overestimate wind speeds during calm conditions, data assimilation was used to nudge modelled

Table 3.1 Sensitivity analysis for determining model parameters for Alexandra for May 2008. Run 1: default settings without data assimilation; Run 2: default settings with data assimilation; Run 3: deep soil temperature and sea surface temperature reduced by 5 °C from default, data assimilation included; Run 4 : parameters of Run 3 with pollution also included; Run 5: parameters of Run 3 with pollution and a fourth grid added. (IOA and RMSE are defined in Section 3.5.3).

Variable	Run	Grids	Min	Max	Mean	St dev	IOA	RMSE
Temperature (°C)	Obs	-	-5.0	17.0	4.3	3.98	-	-
	1	3	-7.3	18.6	6.8	4.42	0.76	4.16
	2	3	-11.3	18.6	6.1	5.44	0.77	4.46
	3	3	-12.5	18.5	5.6	5.59	0.78	4.33
	4	3	-10.3	18.5	5.7	5.51	0.78	4.23
	5	4	-4.9	18.3	6.5	4.29	0.76	4.04
Wind speed (m s^{-1})	Obs	-	0.0	2.8	0.4	0.51	-	-
	1	3	0.1	6.7	1.8	1.01	0.94	1.66
	2	3	0.0	4.2	0.8	0.73	-	-
	3	3	0.0	5.3	0.8	0.75	-	-
	4	3	0.0	5.3	0.8	0.75	-	-
	5	4	0.0	3.1	0.5	0.56	-	-
PM10 (µg m^{-3})	Obs	-	0.0	293.5	60.6	55.03	-	-
	4	3	0.0	0.7	0.0	0.06	0.00	81.60
	5	4	1.3	933.8	111.3	144.33	0.63	143.97

Table 3.2 Data assimilation set-up.

	Alexandra	Mosgiel
Location of monitoring site (m)	+600 (x), +600 (y)	+1300 (x), +2000 (y)
Height of instruments (m)	3	3
Radius of influence (m)	5000	5000
Number of vertical levels	2	2
Data quality indicator (0 – 1)	1	1

results towards observed results in the subsequent runs (Table 3.1). The observational file used for data assimilation consists of wind speed and wind direction values at hourly averages, the location of the monitoring site (in relation to the grid centre), the number of vertical levels to include in the calculations, the height of the instruments, the radius of influence that the data should have, and the quality of the data, with zero indicating that the data should be ignored, through to one indicating that the data are reliable (Hurley 2008b). The data assimilation set-up is shown in Table 3.2.

For each town, the ORC wind data were used. Initially these data were assigned a quality indicator of 0.7 due to the sheltering nature of surrounding buildings, but using this value failed to reduce modelled wind speeds sufficiently, which lead to the quality indicator being increased to one. Only the bottom two vertical levels were selected to assimilate, as wind patterns can change significantly with height, and it is expected that near-surface winds will be of less magnitude than those aloft. The radius of influence for each site was set at 5 km. Hurley (2008b) suggests that this value should be between 5 km and 30 km depending on the terrain, with 20 km being a normal value to use for flat or sloping terrain. Because of the proximity of hills around each town, anything greater than 5 km radius would not have been realistic, especially if it is desirable to capture drainage flows in the model.

It was found that reducing the deep soil temperature and sea surface temperature by 5 °C from the default of 11.4 °C also increased the accuracy of the model, especially once pollution data were added. This was done in run three and subsequent runs thereafter. In run four, pollution data were added, the details of which are provided in Section 3.6.2. However, with only three grids being used, the resolution of the innermost grid (3 km^2) was too coarse to capture PM10 concentrations effectively. Once the fourth grid was added, which had a resolution of 1 km^2, modelled PM10 concentrations improved. In addition to reducing deep soil temperature and sea surface temperature, soil moisture was increased from the default value of 0.15 m^3 m^{-3} to 0.3 m^3 m^{-3} for Mosgiel only. Hurley (2008b) states that 0.15 is an appropriate value to use in regions dominated by sandy clay loam soil and was used for Alexandra, which also has fairly low rainfall (358 mm per year). However, Mosgiel receives almost double the rainfall of Alexandra, at 750 mm per year and is also at a low elevation (20 m above sea level) so is likely to have a greater soil moisture content.

Pollution Module Set-up

The grid spacing for the pollution module was equal to that of the innermost grid of the meteorological module, but with 30 x 30 grid points used. Because of the lack of detail and site specificity of the emissions inventory developed by Wilton (2006), a generic emissions profile developed by Peyman Zawar-Reza at the University of Canterbury was used. With this profile, total daily emissions, estimated by Wilton (2006), are broken down into a value for each hour of the day, and should be representative of any New Zealand town. Vehicular, industrial, and domestic emissions each have their own profile. This emission profile provided a more realistic pattern than that of Wilton (2006), which divides a day into four ‘chunks’ and is based on the burning behaviour of Nelson. The daily emissions profiles are shown in Figure 3.6 below.

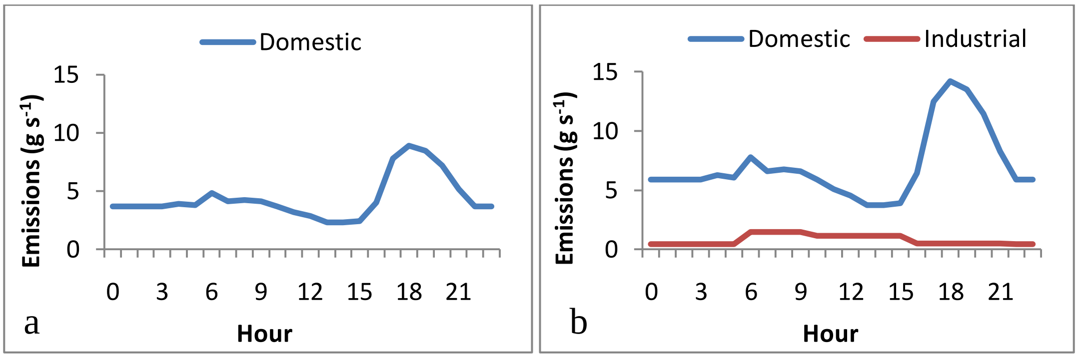

Figure 3.6 Emissions profiles for Alexandra (a) and Mosgiel (b).

Because the 1% industrial contribution to PM10 emissions in Alexandra was deemed negligible, a total value of 380 kg per day was used, with domestic emissions the sole contributor. The size of the source area was set to 1.5 km^2. For Mosgiel, industrial activity accounts for 10% of emissions, with domestic emissions accounting for the remaining 90%. On an average winter day 608 kg of PM10 is emitted into the atmosphere from domestic sources, and the size of the area source was set at 2 km by 2.5 km. The main source of industrial emissions in Mosgiel comes from the Wood Moulding Company to the north of the town which produces 69 kg of PM10 on an average winter day. The wood waste fuelled boiler generates a point source of emissions from a stack at 10 m above ground level with a radius of 600 cm. The exit velocity is 12.42 m s^{-1} on average with an exit temperature of 192 °C (McVie, pers. comm. 2010). The industrial emissions profile from Canterbury University was again used in favour of the emissions inventory by Wilton (2006).

3.5.3 Model Validation

To validate the data produced by TAPM, modelled and observed data should be checked visually as a time series, both at the surface and aloft. Statistical tests should also be carried out to explore the strength of the agreement between modelled and observed data. In this research, two main indicators were used:

Index of agreement (Gimson et al., 2007)

$$\text{IOA} = 1 - \frac{\sum_{i=1}^{N}(P_i - O_i)^2}{\sum_{i=1}^{N}(P'_i - O'_i)^2}$$

$$P'_i = abs(P_i - \bar{O})$$

$$O'_i = abs(O_i - \bar{O}) \qquad \text{(Equation 3.1)}$$

Root mean square error (Gimson et al., 2007)

$$\text{RMSE} = \frac{\sqrt{\sum_{i=1}^{N}(P_i - O_i)^2}}{N} \qquad \text{(Equation 3.2)}$$

where P is the predicted value, O is the observed value and $\bar{O}$ is the mean observed value. The IOA measures the ability of the model to replicate the mean and variability of the observed data (Gimson et al., 2007). For the IOA, zero equals no match and one equals a perfect match, with a value greater than 0.5 generally being considered good (Zawar-Reza et al., 2005). The RMSE is the square root of the mean squared variance of the modelled values, and gives an estimate of the error of the model compared to the observed data. A RMSE which is smaller than the standard deviation of the observed values indicates that precision is being shown by the model (Luhar and Hurley, 2003). However, if a variable has a large standard deviation (such as PM10, which ranges from zero to hundreds) then the RMSE will also be large.

Table 3.1 shows good agreement between observed and modelled meteorological values with all IOAs above 0.5. Interestingly, the index of agreement for wind speed for run one (without data assimilation) was 0.94 despite the fact that the observed mean was 0.4, whereas the modelled mean was 1.8. This may be because trends in wind speed were captured well by the model, rather than it replicating exact magnitudes. Once data assimilation has been added, validation statistics cannot be used for wind speed, as the observational data have been given to the model and the resulting agreement between the observations and the model output should be very close. The final model set-up that was used needed to strike a balance between modelling the meteorology well, but, and more importantly, pollution concentrations also needed to be modelled well. Therefore, run five was used, with the following parameters: four grids with 35 x 35 grid points and an innermost grid resolution of 1 km, data assimilation of wind speed and wind direction, sea surface temperature and deep soil temperature both at 6.4 °C, and soil moisture at 0.15 $m^3 m^{-3}$ for Alexandra and 0.3 $m^3 m^{-3}$ for Mosgiel. Alexandra had a single area source and Mosgiel had a single area source and a single point source for PM10 emissions, corresponding to domestic and industrial emissions respectively.

3.6 Summary

The two Otago towns of Alexandra and Mosgiel are either mostly or fully surrounded by hills that shelter them from synoptic winds. The use of domestic heating appliances is high in each town, and under calm wintertime conditions dispersion of domestic emissions is poor. This research makes use of both existing datasets and numerical modelling to shed light on the air pollution meteorology of each town. In the next chapter, an overview of the observational results from 2007 - 2009 will be presented.

4

Observational Results

4.1 Introduction

In this chapter, the results from the observational data are presented. Trends in the breaches occurring in each town since monitoring began are shown, before focussing on the three year dataset from 2007 - 2009 for the remainder of the chapter. Observational results for Alexandra are presented first, followed by Mosgiel.

4.2 Alexandra

4.2.1 Trends in PM10, 1999 - 2009

PM10 air pollution in Alexandra has been monitored sporadically since 1997 with either one day in six or one day in three sampled. For this, a Hi-Vol sampler was used which gives a total concentration of PM10 for a 24 hour period. Since 2005 however, a permanent monitoring site has been in operation, providing hourly averaged meteorological variables of temperature, wind speed and wind direction. PM10 data have also been collected hourly since 2005 using a Beta Attenuation Monitor (BAM) (Otago Regional Council, 2005).

Figure 4.1 shows that the NES for PM10 is exceeded 30 – 75 times each winter in Alexandra. A gradual increase in breaches from 1999 to 2004 is evident, followed by a decrease from 2004 to 2007, with an exceptionally high number of breaches occurring in 2008. Overall, from this dataset, it is difficult to determine whether the number of

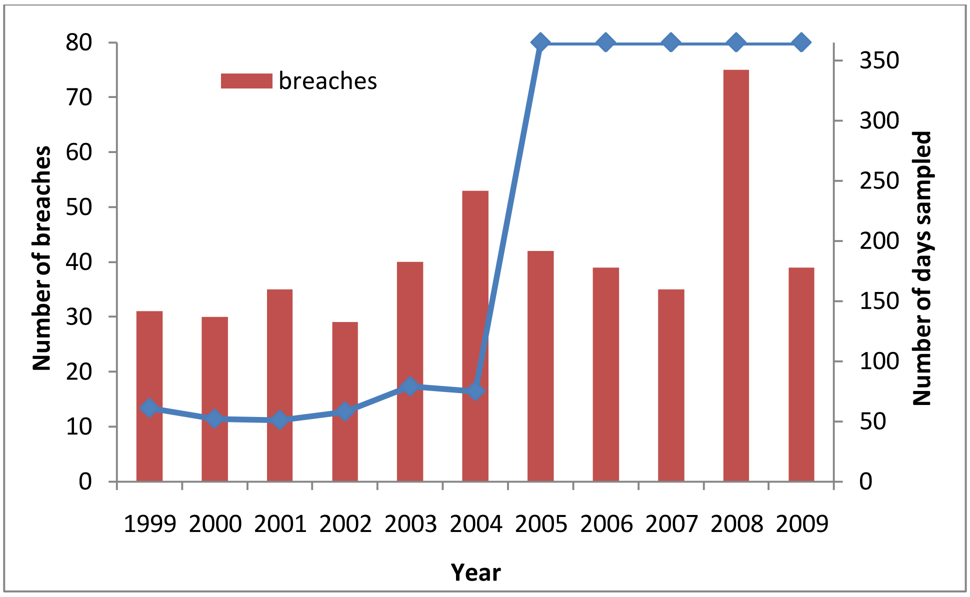

Figure 4.1 Number of breaches and number of days sampled per year from 1999 to 2009 for Alexandra.

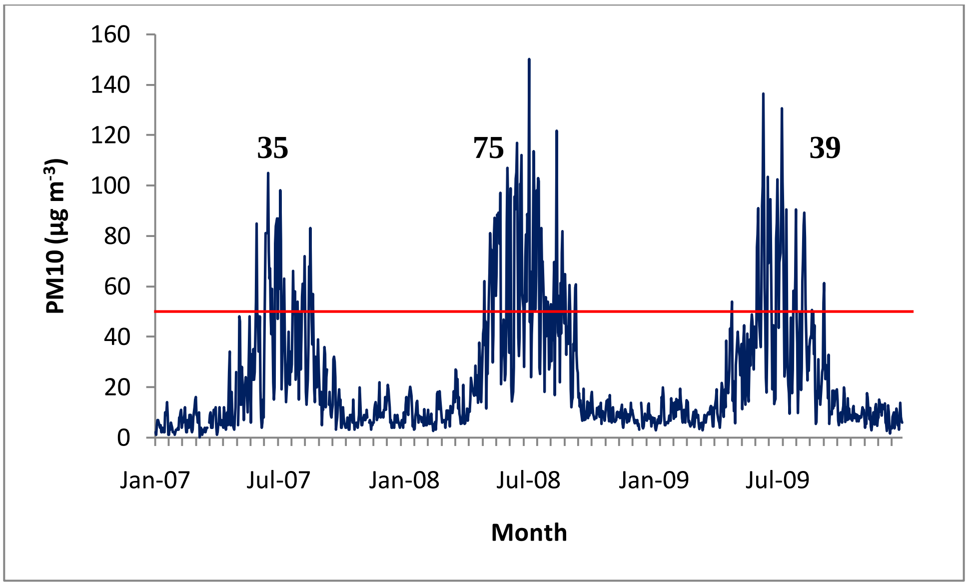

Figure 4.2 Daily average PM10 levels for Alexandra from 2007 - 2009, the red line represents the NES and the numbers are the number of breaches that occurred each year.

breaches is increasing or decreasing in Alexandra. It is also difficult to determine whether inter-annual variations have resulted from changes in emission rates, changes in sampling, or from varying meteorological conditions that influence dispersion.

4.2.2 Climatic and Air Pollution Trends, 2007 - 2009

The maximum daily average for PM10 over the last three years was 150 µg m^{-3} and occurred in the winter of 2008. From Figure 4.2 it can again be seen that significantly more breaches occurred in 2008 than 2007 or 2009. Over the past three years Alexandra has averaged 50 breaches per year. There is a strongly seasonal trend in PM10 levels, with daily levels mostly below 20 µg m^{-3} during the summer months. PM10 levels increase gradually through autumn, peak in winter and decrease again through spring.

The increase in PM10 levels in winter coincides with a decrease in both air temperature and wind speed, as shown in Figure 4.3. (Please note that Figure 4.3d, e, and f for

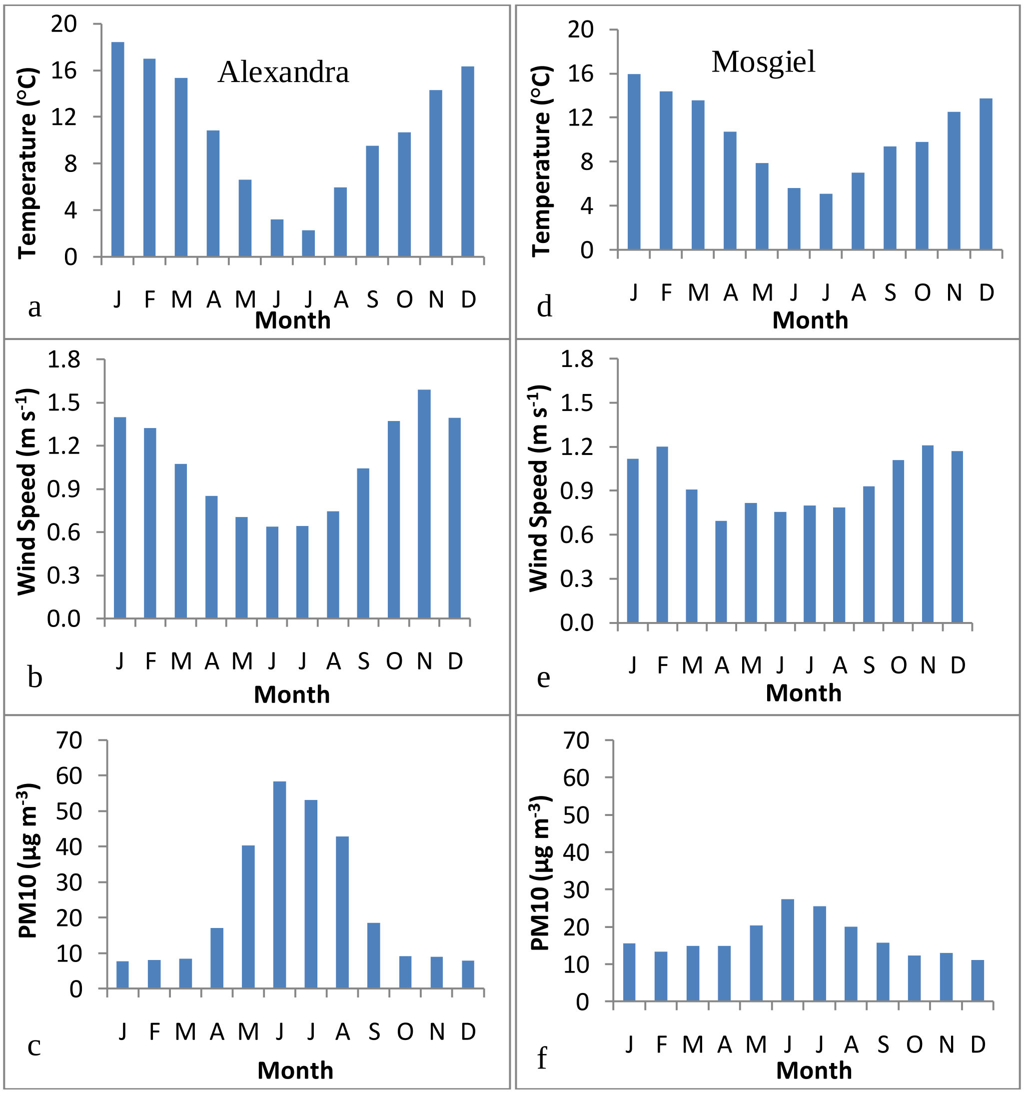

Figure 4.3 Monthly ensembles for temperature (a,d), wind speed (b,e), and PM10 (c,f) for Alexandra and Mosgiel from 2007 to 2009. For Discussion of Mosgiel plots see Section 4.3.

Mosgiel are discussed in Section 4.3 but have been displayed in this section so that the two towns can be compared. The same applies for Figure 4.6.) There is an inverse relationship between both PM10 and temperature, and PM10 and wind speed. June and July have the highest values for PM10, which coincides with the lowest temperatures and wind speeds of the year. Interestingly, June has higher PM10 levels than July (Figure 4.3c), despite experiencing slightly higher air temperatures (Figure 4.3a).

The inverse relationship between PM10 and temperature and PM10 and wind speed is again evident in the scatterplots shown in Figure 4.4a and b. The relationship between PM10 and temperature is strongest, with changes in temperature accounting for 48% of the variance in PM10 (Figure 4.4a), whereas variability in wind speed accounts for 39% of the variance in PM10 (Figure 4.4b).

As shown in Figure 4.5, wind speeds in Alexandra are fairly light, with most wind speeds falling below 2 m s^{-1}, and, on an annual basis, Alexandra does not appear to have a dominant wind regime. However, most winds greater than 2 m s^{-1} come from the north-east, and most winds less than 0.5 m s^{-1} come from the north-west (Figure 4.5a). When looking at the wind regime for the winter months only, it is again evident that there is a higher frequency of low wind speeds from the northwest (Figure 4.5b).

The stronger winds from the north-east do not occur during winter, which indicates that they may be stronger thermotopographic winds generated by surface heating in summer, although it is important to remember that the sheltered nature of the monitoring site and the height of the instruments compromises the quality of the data somewhat. Wind roses created from data from the NIWA monitoring site approximately six kilometres to the north-west of Alexandra (see Appendix A for these) also failed to show a dominant wind regime at an annual scale. In winter there was a higher frequency of light wind speeds (less than 0.5 m s^{-1}) from the north than from any other direction, which may be drainage flows from the Clutha Gorge. Thus, it can be concluded that the wind regime in Alexandra is driven more by surface energetics than by synoptic winds, which results in low wind speeds, especially in winter. This is to be expected, as low wind speeds are a precursor to high pollution events.

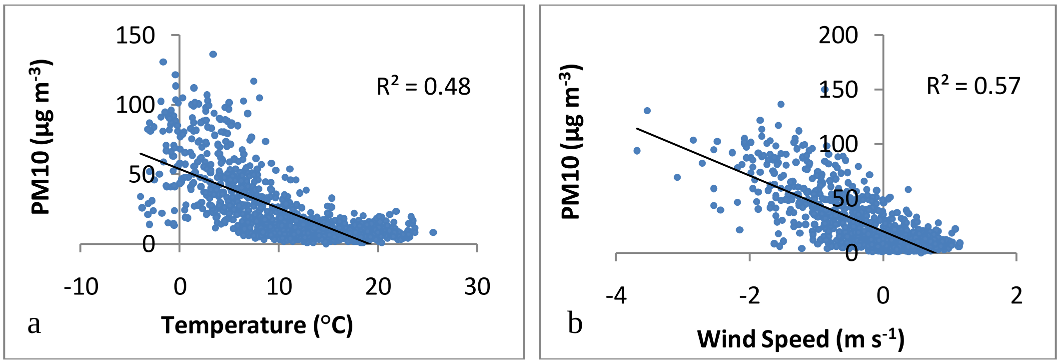

Figure 4.4 Scatterplots of daily averaged PM10 versus temperature (a), and PM10 versus wind speed (b) for Alexandra from 2007 - 2009.

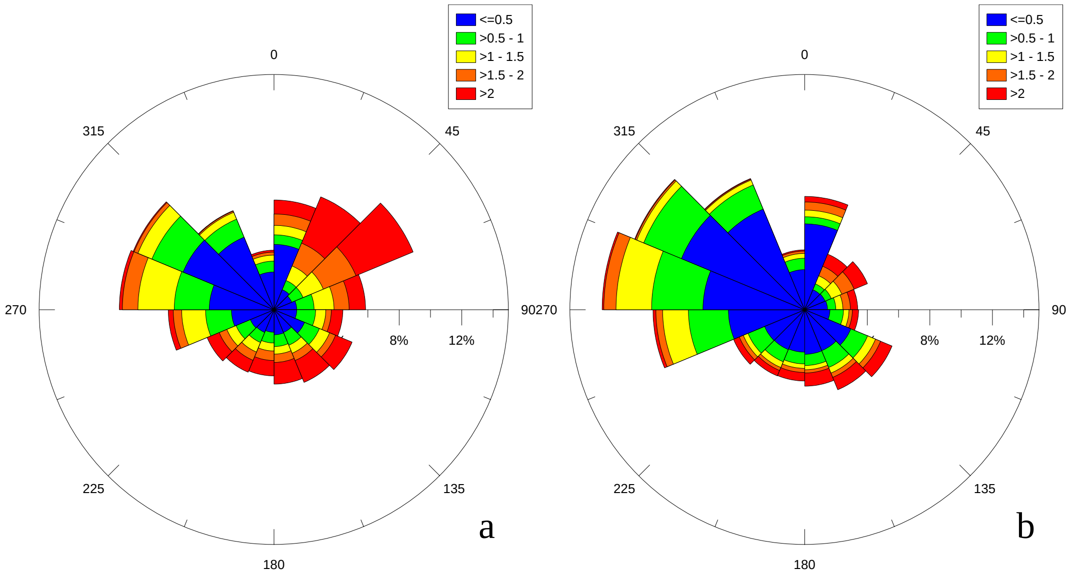

Figure 4.5 Wind roses for Alexandra using all hourly averaged wind data (a) and winter hourly averaged wind data only (b) from ORC data from 2007 – 2009.

Diurnally, high pollution days in Alexandra follow a fairly typical trend, with a morning peak at 0900 hours and an evening peak at 1900 hours (Figure 4.6a). However, after the peak at 1900 hours, PM10 levels decrease again over the next three hours before reaching a third peak at 2300 hours, followed by a gradual decrease through the night until 0700 hours. Lowest hourly values on high pollution days occur at 1400 and 1500 hours which indicates that convective mixing is still occurring during the warmest part of the day. Therefore, the biggest contribution to PM10 levels is occurring during the hours of darkness when emissions are highest and the atmosphere is the most stable.

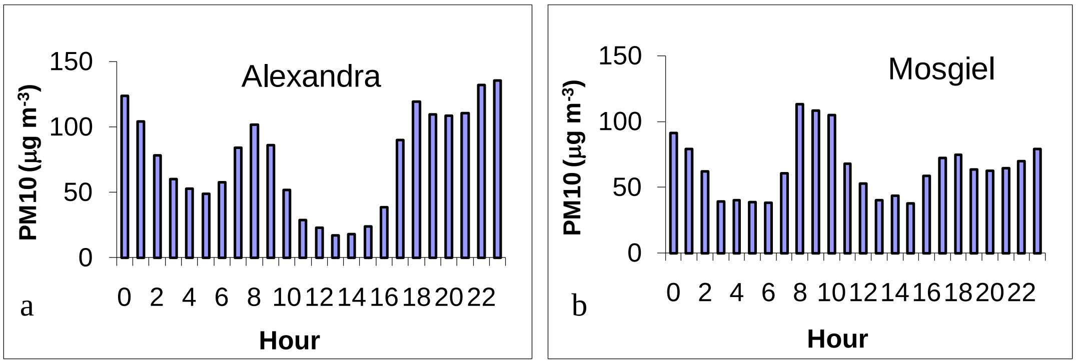

Figure 4.6 Diurnal ensembles for 149 high pollution days in Alexandra (a) and 20 high pollution days in Mosgiel (b) from 2007 to 2009.

4.3 Mosgiel

4.3.1 Trends in PM10, 2001 - 2009

In Mosgiel, air pollution monitoring of PM10 has taken place intermittently since 1998 by way of either a Mini-Vol or a High-Vol sampler. Like Alexandra, a permanent site has been in operation since 2005, with temperature, wind speed, wind direction, and PM10 being measured at hourly averages. Figure 4.7 shows an increase in the number of breaches from zero in 2001 through to 30 in 2004. However, because the number of days sampled per year is relatively low, it is difficult to determine whether the days sampled are representative of the entire year. Since continuous sampling began in 2005 the number of breaches has decreased in 2006 and 2007 before increasing again in 2008. Like Alexandra, a distinct trend in the number of exceedances per year is difficult to observe from this dataset.

4.3.2 Climatic and Air Pollution Trends, 2007 - 2009

Mosgiel's air pollution problem is also restricted to the winter months (Figure 4.8), although there are far fewer breaches here despite the greater population size. Approximately 10% of emissions in Mosgiel are industrial with the remaining 90% from domestic sources. Because of this, PM10 levels are slightly higher during the summer months than in Alexandra where emissions are solely domestic. The high pollution days are also spread quite widely across the winter months, and moderate pollution days (35-50 µg m^{-3}) are not unusual in spring and autumn. Mosgiel has had

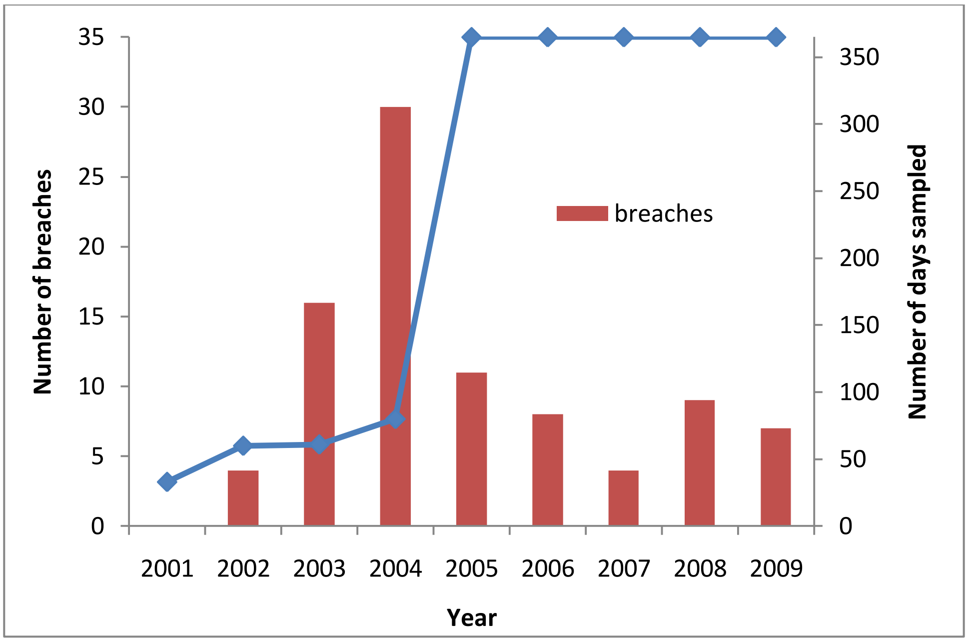

Figure 4.7 Number of breaches and number of days sampled per year from 2001 to 2009 for Mosgiel.

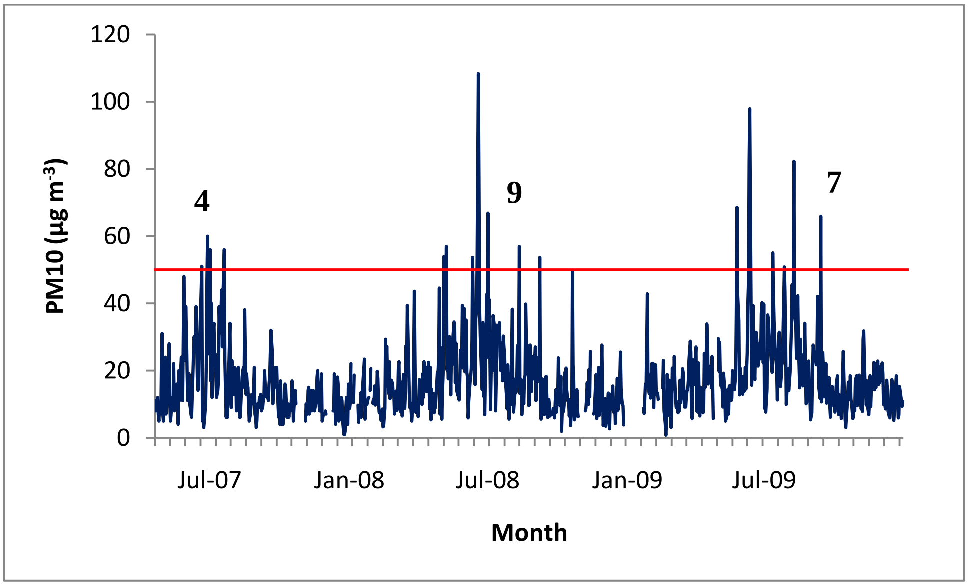

Figure 4.8 Daily average PM10 levels for Mosgiel from 2007 to 2009, the red line represents the NES and the numbers are the number of breaches that occurred each year.

an average of seven breaches per year from 2007 - 2009, with significantly more breaches occurring in 2008 than 2007 or 2009. The highest breach occurred in June of 2008, reaching 108 µg m^{-3}.

PM10 levels in Mosgiel also display an inverse relationship with air temperature (Figure 4.3d and f) and a weaker relationship with wind speed (Figure 4.3e) which has less variation across the year with a lower maximum and a higher minimum than Alexandra. June and July are the worst months for air pollution, which is also when air temperatures are lowest. Compared to Alexandra, temperatures are warmer in Mosgiel and pollution levels lower during winter. Scatterplots also show a weaker relationship between meteorology and pollution in Mosgiel than in Alexandra, with changes in temperature accounting for 13% of the variance in PM10 (Figure 4.9a), and wind speed accounting for 11% of the variance in PM10 (Figure 4.9b).

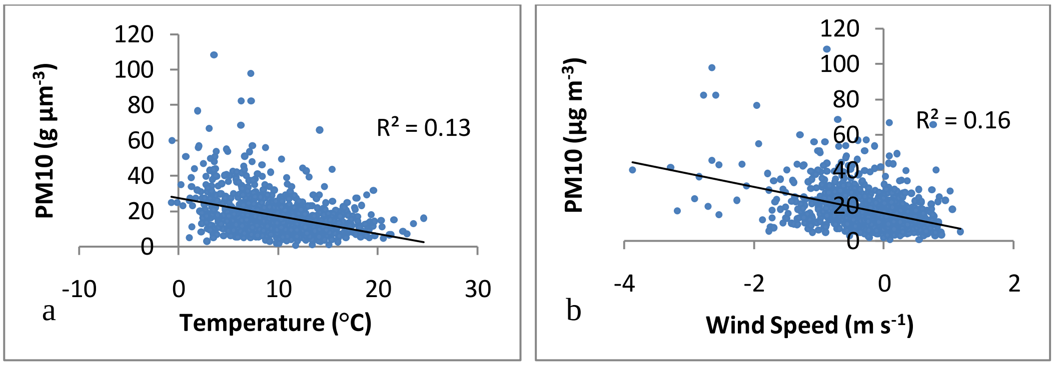

Figure 4.9 Scatterplots of daily averaged PM10 versus temperature (a), and PM10 versus wind speed (b) for Mosgiel from 2007 - 2009.

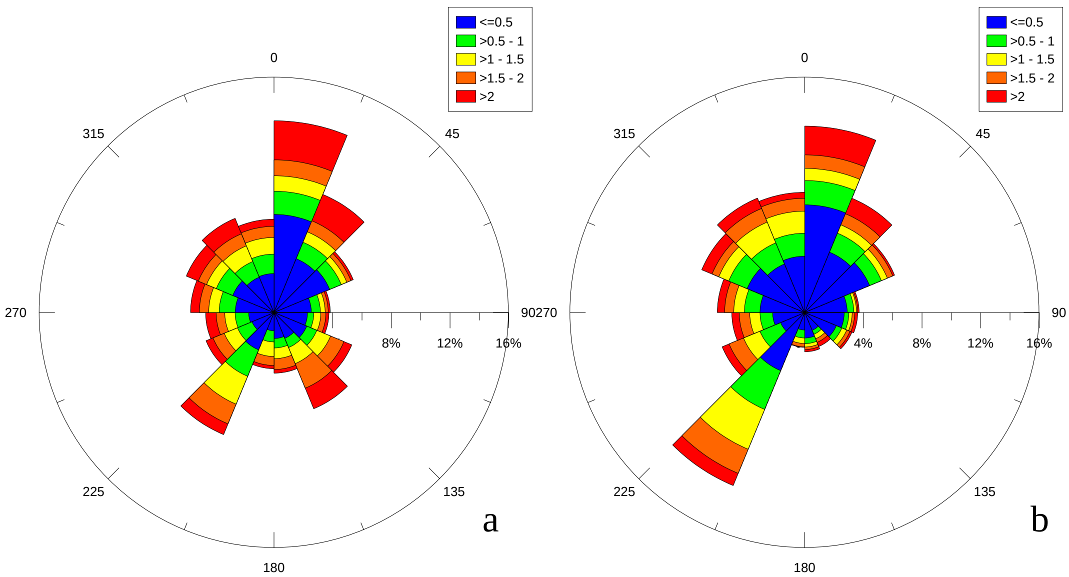

Figure 4.10 Wind roses for Mosgiel using all hourly averaged wind data (a) and hourly averaged winter wind data only (b).

At an annual scale, the most dominant wind direction in Mosgiel is from the north, followed by the south-west (Figure 4.10), in accordance with the axis of the broad valley. This trend is also apparent when observing the wind regime for the winter months only. Very little wind comes from the south-east which is probably due to the proximity of the hills in this direction and the shelter they provide. Winter wind speeds are higher in Mosgiel than in Alexandra, but are still low enough to facilitate moderate PM10 concentrations. Also, the south-west winds that are displayed on both wind roses are likely to be channelled synoptic winds as this is the only direction in which Mosgiel is not sheltered by hills, whereas the winds from the north-east could be both channelled synoptic winds and drainage winds.

The diurnal ensemble for PM10 in Mosgiel shown in Figure 4.6b is somewhat different from that of Alexandra, with the main peak for the day occurring in the morning at 0900 hours. The evening peak at 1900 is relatively small, after which time PM10 levels decrease until 2100 hours before increasing to a second peak at 0100 hours, to then decrease through the remainder of the night. It is important to note that the diurnal ensemble for Mosgiel is composed of only 20 high pollution days compared to 149 at Alexandra. Thus, if there were more high pollution days, the diurnal trend may look different. Another reason that the evening peak in PM10 in Mosgiel is comparatively small may be due to drainage flows moving cleaner air over the monitoring site at night time, with the highest concentrations being transported to the western parts of the town (Otago Regional Council, 2009b). This will be discussed further in Chapter Six.

4.4 Summary

The two southern towns of Alexandra and Mosgiel both experience breaches of the NES on a regular basis during the winter months. However, based on the available data, it is difficult to determine whether the number of breaches is increasing or decreasing. It is likely that the emissions for each town have remained fairly constant over the study period, with the variation in the number of breaches per year reflecting the over-riding synoptic situation. PM10 concentrations show an inverse relationship with both temperature and wind speed, although this relationship is stronger in Alexandra than in Mosgiel. Wind speeds are fairly low annually, and especially in winter, and appear to be caused by surface energetics rather than synoptic winds. Diurnally, patterns of PM10 on high pollution days follow a fairly normal pattern in Alexandra, with peaks in the morning and evening, and lowest concentrations in the afternoon. For high pollution days in Mosgiel, the biggest peak in PM10 concentrations occurs in the morning, with a smaller peak in the evening, although this may be because the evening peak is not being captured well by the monitor. Modelling results, presented in the following chapter will further investigate likely causes of these patterns.

5

Modelling Results

5.1 Introduction

In this chapter the results from the modelling are presented. TAPM was run for the winter of 2008 (1 May – 31 August, a total of 123 days) for each town using the model set-up and parameters that were found to give the best result for both meteorology and pollution concentrations; these are described in Section 3.5.2. The winter of 2008 was selected for modelling for two reasons: firstly, more breaches were experienced in 2008 than in 2007 or 2009, and because this research is aimed at gaining a better understanding of the air pollution meteorology of high pollution events, it made sense to model a winter when a large number of breaches occurred. The second reason for modelling the winter of 2008 was because spatial PM10 data from DustTrak sampling existed for both towns. Therefore, TAPM could be tested against existing spatial PM10 data to determine whether it was simulating pollution dispersion patterns effectively. The results of these tests will be presented as case studies, after the results for the whole winter are presented. Once again, the modelling results for Alexandra are presented first, followed by Mosgiel.

5.2 Alexandra

Air temperatures in Alexandra were modelled well for the winter period (Figure 5.1a), with an overall mean temperature of 5.8 °C, which was 1.5 °C warmer than the observed mean temperature of 4.3 °C (Table 5.1). The IOA between observed and modelled air temperatures was good at 0.74, and the RMSE is approximately the same

Table 5.1 Summary and validation statistics for observed and modelled temperature, wind speed, and PM10 for the winter of 2008 for Alexandra. Observational data are from the ORC monitoring site.

Variable		Min	Max	Mean	St dev	IOA	RMSE
Temperature (°C)	Observed	-6.3	17.5	4.3	4.52	-	-
	Modelled	-7.6	18.3	5.8	4.05	0.74	4.18
Wind Speed (m s^{-1})	Observed	0	4.7	0.6	0.70	-	-
	Modelled	0	5.4	0.6	0.76	-	-
PM10 (µg m^{-3})	Observed	0	385.8	60.2	56.26	-	-
	Modelled	1.2	933.8	85.1	112.94	0.67	118.28

as the standard deviation of the observed data, which indicates that modelled variability is similar to observed variability.

Mean modelled wind speeds were the same as observed (Figure 5.1b) at 0.6 m s^{-1}. The agreement between the observed and modelled wind speeds is due to the effect of data assimilation, which nudged modelled values towards observed values. Because data assimilation was used, validation statistics could not be performed for wind speed. Without data assimilation, modelled wind speeds were too high, which resulted in modelled PM10 levels being too low.

Mean modelled PM10 concentrations for the winter of 2008 were 85.1 µg m^{-3}, which was 15 µg m^{-3} greater than the observed mean of 60.2 µg m^{-3} (Table 5.1). Thus, PM10 concentrations were over-predicted by 41%. The IOA was 0.67, which indicates that the agreement between observed and modelled concentrations is good. However, the RMSE was a lot greater than the standard deviation of the observed values, which indicates that the model was producing more variability than the observational data. This is also evident when looking at the time series (Figure 5.1c) and the maximums for PM10 (Table 5.1), which show that TAPM simulated hourly PM10 concentrations as high as 933.8 µg m^{-3}, which was 550 µg m^{-3} higher than the observed maximum, and unlikely to be realistic.

When looking at the model output on individual days, it was observed that the model had a tendency to simulate large spikes in hourly PM10 which normally occurred at around 1900 hours and only lasted for one hour before returning to more normal levels.

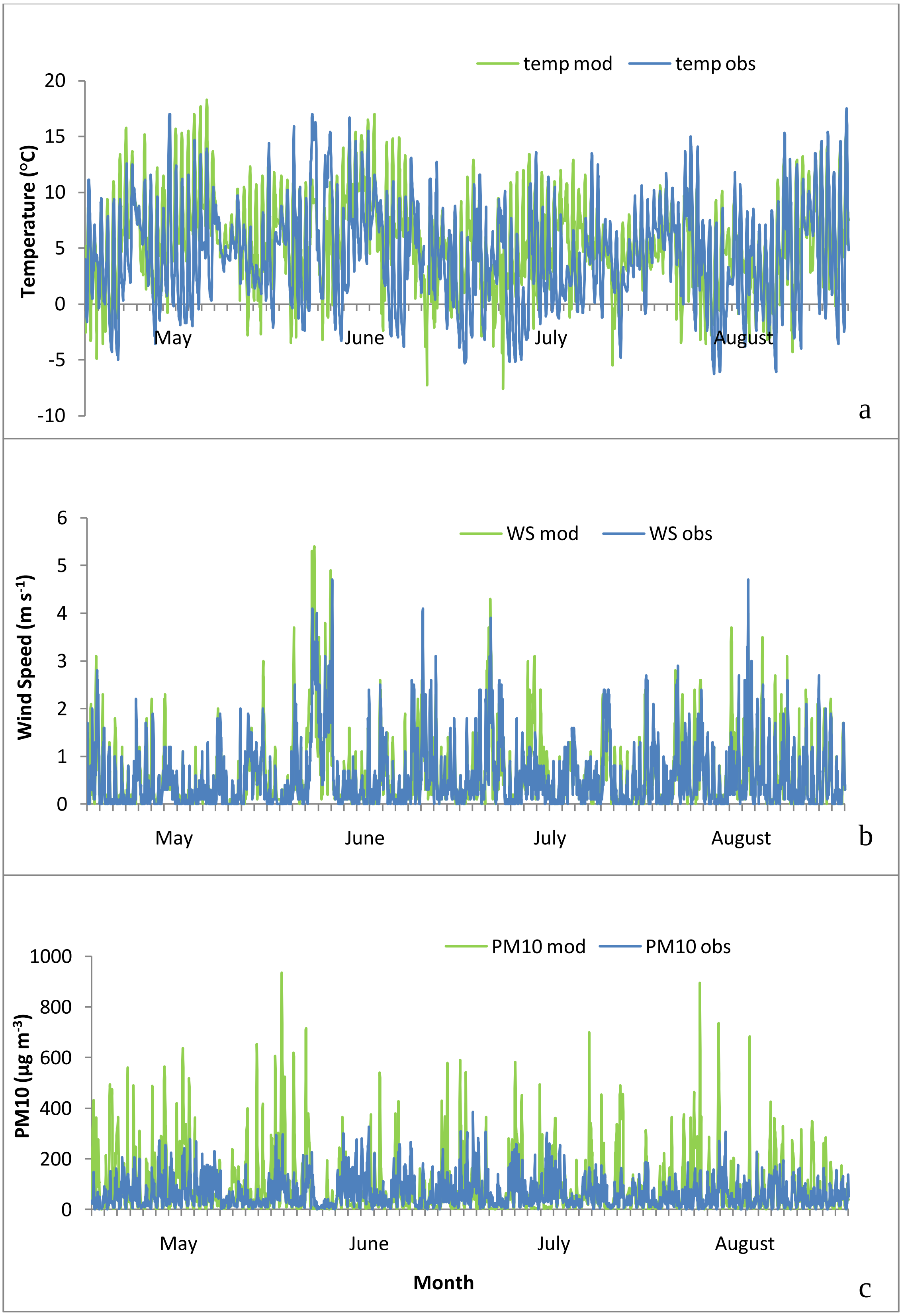

Figure 5.1 Time series of observed versus modelled hourly temperature (a), wind speed (b), and PM10 (c) for Alexandra for the winter of 2008. Observational data are from the ORC monitoring site.

A test run with an emissions profile that was constant across the day gave the same result, so it can therefore be assumed that at this time of the day the model is over-exaggerating either the effect of the drainage flows, the stability of the atmosphere, or both.

To test how well TAPM was able to reproduce breaches and non-breaches of the NES, daily averages for PM10 were generated from the model output and compared with observed daily averages. It was found that TAPM was able to correctly predict 56 out of the 72 breaches that occurred in Alexandra in the winter of 2008, while the remaining 17 breach days were modelled as having a daily average below 50 µg m^{-3}. Of the 51 non-breach days, 25 were correctly modelled as non-breaches and 25 were incorrectly modelled as breaches (Table 5.2). Overall, 66% of the days were modelled correctly by TAPM, and the remaining 34% were incorrectly modelled.

Table 5.2 Model accuracy for correctly predicting breaches and non-breaches of the NES for PM10 in Alexandra.

	Breaches correctly predicted	Non-breaches correctly predicted	Observed breach not modelled	Non-breach modelled as breach	Total correctly predicted	Total incorrectly predicted
Alexandra	56/72 (78%)	25/51 (49%)	17/72 (24%)	25/51 (49%)	81/123 (66%)	42/123 (34%)

To determine whether TAPM was accurately simulating meteorological and air pollution trends at a diurnal scale on breach days, daily ensembles were created using only the high pollution days that were correctly forecast. These ensembles were then plotted against the observed data for the same days. Figure 5.2 shows that modelled air temperature follows the same general trend as observed air temperature, but modelled temperatures are approximately 2 °C warmer for all times of the day except between 1600 and 1800 hours when they are slightly cooler than observed temperatures.

When looking at the diurnal ensemble for observed and modelled high pollution days (Figure 5.3) it is clear that TAPM is over predicting PM10 levels in the evening between 1900 and 2200 hours and again between 0200 and 0900 hours, with modelled levels lower than observed during the daytime between 1100 and 1600 hours. The

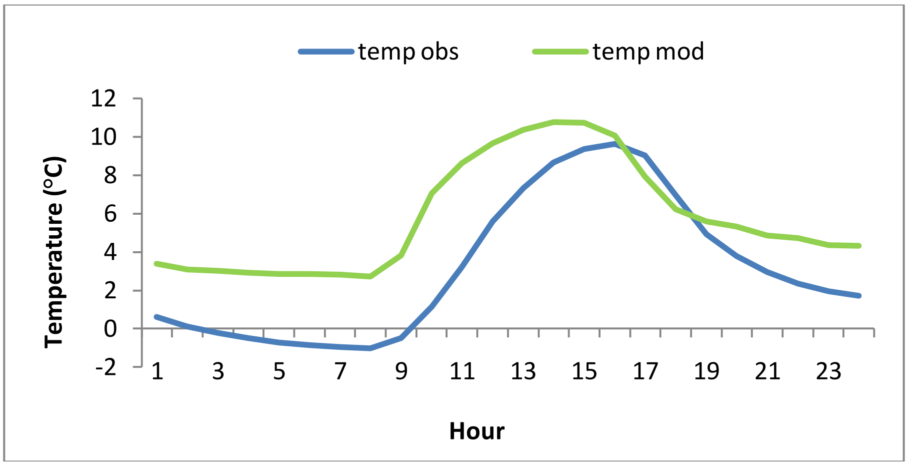

Figure 5.2 Diurnal temperature ensemble for high pollution days (n=56) correctly modelled by TAPM.

greatest error between modelled and observed PM10 levels occurs at 2000 and 2100 hours. This may again be a result of TAPM's tendency to over-exaggerate cold air drainage flows, which would transport pollution from higher to lower elevations, thus increasing pollution levels at lower elevations. Also, if TAPM was modelling an atmosphere that was strongly stable, pollution would be trapped near the surface which would again result in higher concentrations. Another reason for the modelled concentrations being higher than observed concentrations may be that Wilton's (2006) daily emissions value was too high.

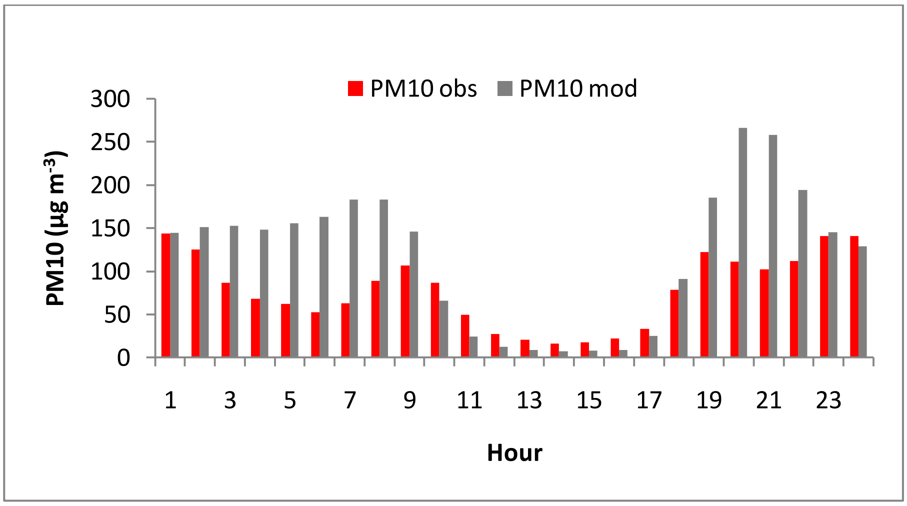

Figure 5.3 Diurnal PM10 ensemble for high pollution days (n=56) correctly modelled by TAPM for.

5.3 Mosgiel

Air temperatures in Mosgiel were modelled well over the winter of 2008, with less than 1 °C difference between the modelled mean of 5.9 °C and the observed mean of 6.3 °C (Table 5.3). Interestingly, modelled air temperatures in Mosgiel were slightly lower than observed air temperatures, whereas in Alexandra, modelled air temperatures were slightly higher than observed. This may be because one of the parameters of the model set-up for Mosgiel was to increase soil moisture content to 0.3 m^3 m^{-3} to reflect the low elevation and the greater rainfall experienced there, whereas soil moisture for Alexandra was left at the default setting of 0.15 m^3 m^{-3}. At 0.89, the IOA between observed and modelled air temperatures was high, indicating that the agreement is very good. The RMSE is also small, which indicates that the model is performing with precision.

Table 5.3 Summary and validation statistics for observed and modelled temperature, wind speed, and PM10 for the winter of 2008 for Mosgiel. Observational data are from the ORC monitoring site.

Variable		Min	Max	Mean	St dev	IOA	RMSE
Temperature (°C)	Observed	-3.8	18.3	6.3	3.82	-	-
	Modelled	-6.1	16.6	5.9	3.77	0.89	2.65
Wind Speed (m s^{-1})	Observed	0.0	4.4	0.8	0.75	-	-
	Modelled	0.0	6.5	1.3	1.14	-	-
PM10 (µg m^{-3})	Observed	0.0	326.7	25.1	30.87	-	-
	Modelled	1.0	927.4	37.1	81.73	0.35	84.92

When viewed as a time series (Figure 5.4a), modelled air temperatures are often lower at night, and the overall mean is also lower. This may indicate that soil moisture was too high in Mosgiel, as a high soil moisture value would result in more evaporation during the day, resulting in lower air temperatures. This will be discussed further in Chapter Six.

The agreement between observed and modelled wind speeds in Mosgiel was not as good as for temperature. Mean modelled wind speeds over the winter period were 1.3 m s^{-1}, which was higher than the observed mean of 0.8 m s^{-1} (Table 5.3). When viewed as a time series (Figure 5.4b) it can be seen that the model is following the trends in

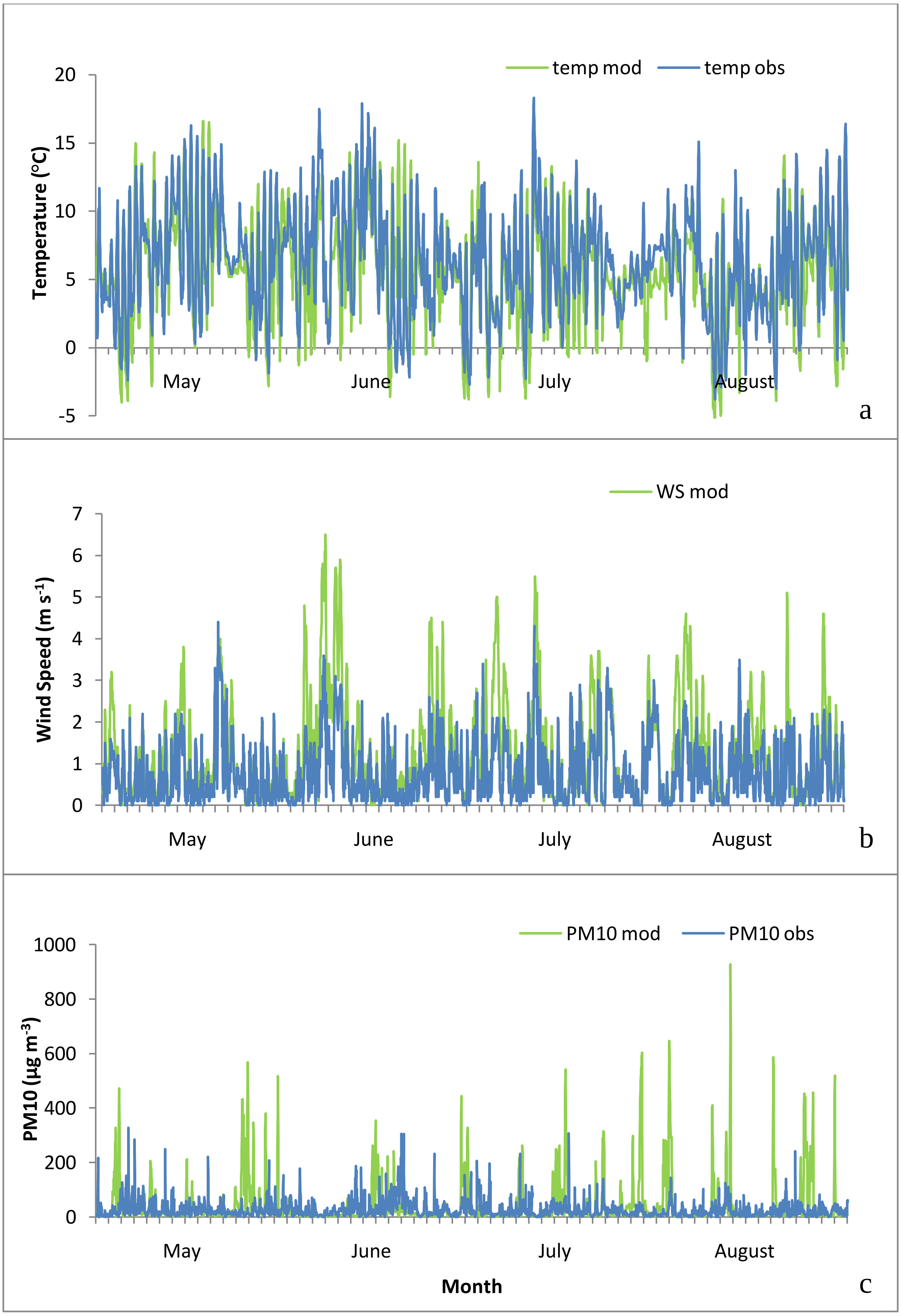

Figure 5.4 Time series of observed versus modelled hourly temperature (a), wind speed (b), and PM10 (c) for Mosgiel for the winter of 2008. Observational data are from the ORC monitoring site.

Table 5.4 Model accuracy for correctly predicting breaches and non-breaches of the NES for PM10 in Mosgiel.

	Breaches correctly predicted	Non-breaches correctly predicted	Observed breach not modelled	Non-breach modelled as breach	Total correctly predicted	Total incorrectly predicted
Mosgiel	1/9 (11%)	86/114 (75%)	8/9 (89%)	28/114 (25%)	87/123 (71%)	36/123 (29%)

wind speed well, but is over-predicting maximum wind speeds despite the assimilation of observed wind speed and wind direction data.

Mean modelled PM10 levels for the winter of 2008 in Mosgiel were 37 µg m^{-3}, which is 12 µg m^{-3} greater than the observed mean of 25 µg m^{-3}, and an over-prediction of 48%. However, as with Alexandra, large spikes in hourly PM10 levels were simulated by TAPM; Table 5.3 shows the modelled maximum PM10 value to be 600 µg m^{-3} greater than the observed maximum. Because of this, the IOA is relatively low at 0.35 and the RMSE is relatively high. When viewed as a time series (Figure 5.4c) it is clear that the trend in observed PM10 values has not been well captured by the model. The reasons for this are largely unknown, as the physical processes of cold air drainage and temperature inversions that facilitate pollution build-up should occur in a similar manner in each town. Also, with TAPM over-predicting wind speeds in Mosgiel it would be expected that this would reduce PM10 levels through increased turbulence. Instead, the opposite has occurred, with modelled concentrations often higher than those observed. This may also be related to an inaccuracy in the daily emission value that was used. During the winter of 2008, nine breaches of the NES occurred in Mosgiel. Of these nine breaches, only one was correctly modelled by TAPM, with the remaining eight modelled as having a daily average below 50 µg m^{-3} (Table 5.4). Of the 114 non-breach days, 86 were correctly modelled by TAPM, with the remaining 28 days incorrectly modelled as breach days. Overall, TAPM modelled correctly 71% of the time, and incorrectly 29% of the time. However, because TAPM failed to capture most of the observed breaches, there is little confidence in using the model to provide insight into processes occurring on high pollution days.

5.4 Summary of Model Performance

TAPM was used to model meteorological conditions and PM10 concentrations for the winter of 2008 in both Alexandra and Mosgiel. Temperature and wind speed were generally modelled well in both towns, although modelled wind speeds were slightly too high for Mosgiel. Breach days were modelled better in Alexandra than in Mosgiel with 78% of breach days correctly modelled and 66% of days correctly modelled overall. Only one of the nine breach days in Mosgiel was correctly modelled, although, overall, TAPM modelled correctly 71% of the time, which is due to a large number of non-breach days being correctly modelled. At a diurnal scale, modelled conditions matched observed conditions well in Alexandra on breach days, with the main discrepancy being that modelled PM10 concentrations were greater than observed concentrations through most of the night. Insight into diurnal processes on high pollution days in Mosgiel could not be made since only one breach was correctly predicted.

The aim of the following section is to investigate how TAPM is performing over smaller temporal scales, thus shedding light on atmospheric processes and topographical influences on air pollution concentrations in the two towns. This is achieved through a series of case studies, so that the spatial and temporal patterns in air pollution meteorology can be examined at hourly and daily scales. The first is a ten day case study of Alexandra in June, the second is a single day case study of Alexandra in August, and the third is a single day case study of Mosgiel in August.

5.5 Case Study One: Alexandra, 21 – 30 June 2008

As well as comparing the model output with observational data, this case study compares DustTrak spatial PM10 data collected over a 10 day period in June 2008 by West (2008) with the model output for the same time period. The synoptic situation at the beginning of this ten day case study (Figure 5.5) shows an anticyclone moving eastwards away from the South Island, although a ridge of high pressure still extends over the country. A cyclone and associated warm and cold fronts are approaching from the west, as well as two cold fronts from the south-west. By 24 June the cyclone and fronts have passed over the country bringing about a southerly change, although a complex area of low pressure persists over the South Island over the following days. By

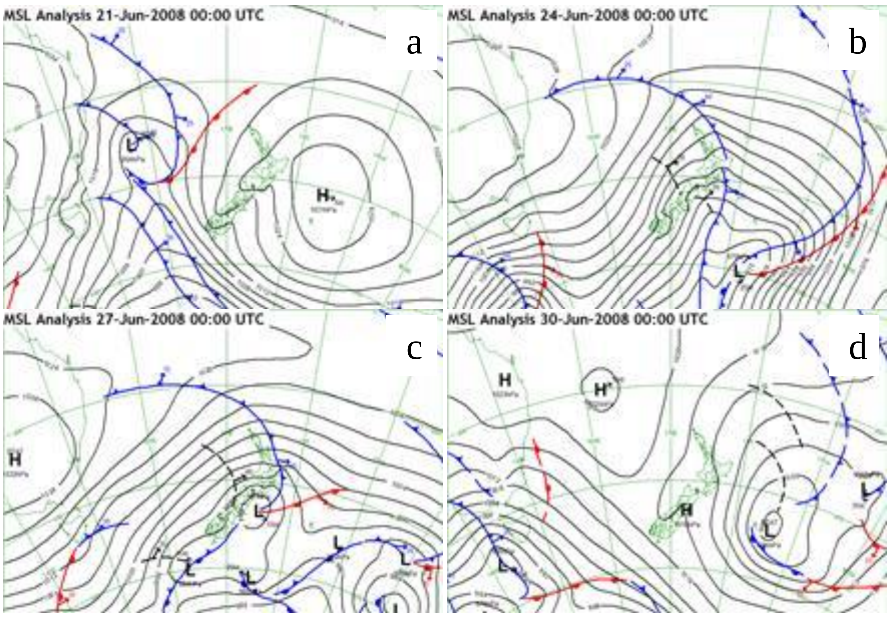

Figure 5.5 Synoptic situation for 21 June (a), 24 June (b), 27 June (c), and 30 June (d) 2008 at 1200 hours NZST.

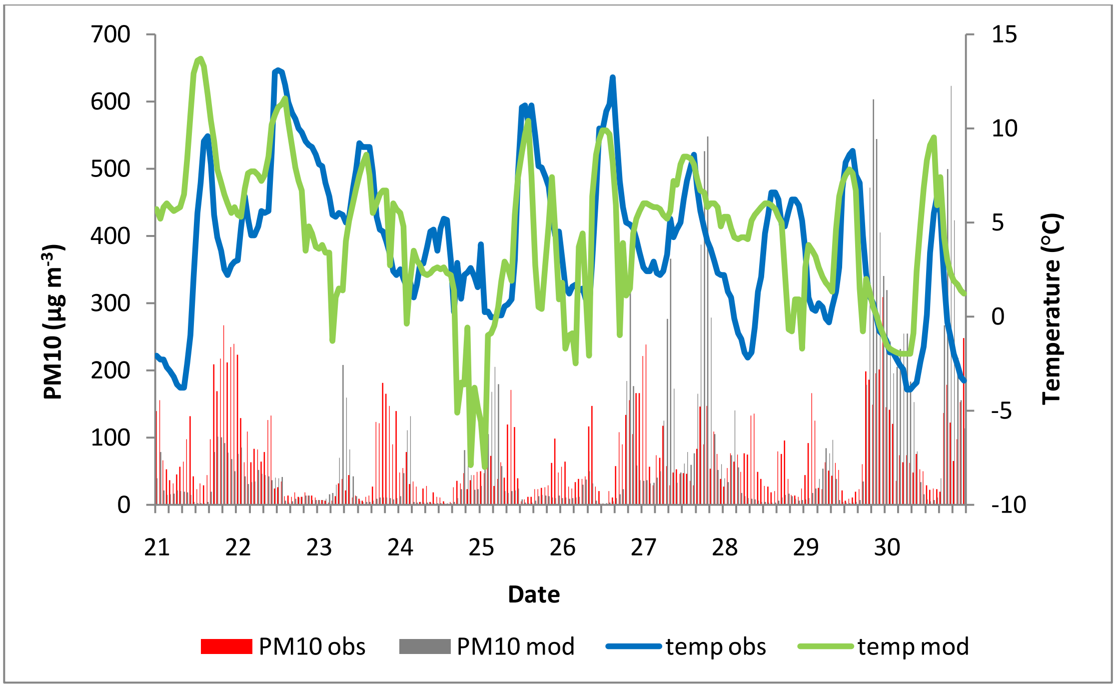

Figure 5.6 Time series of observed and modelled PM10 and observed and modelled temperature for 21 – 30 June 2008 in Alexandra. Observational data are from the ORC monitoring site.

30 June the low pressure system has moved eastwards and been replaced by another ridge of high pressure.

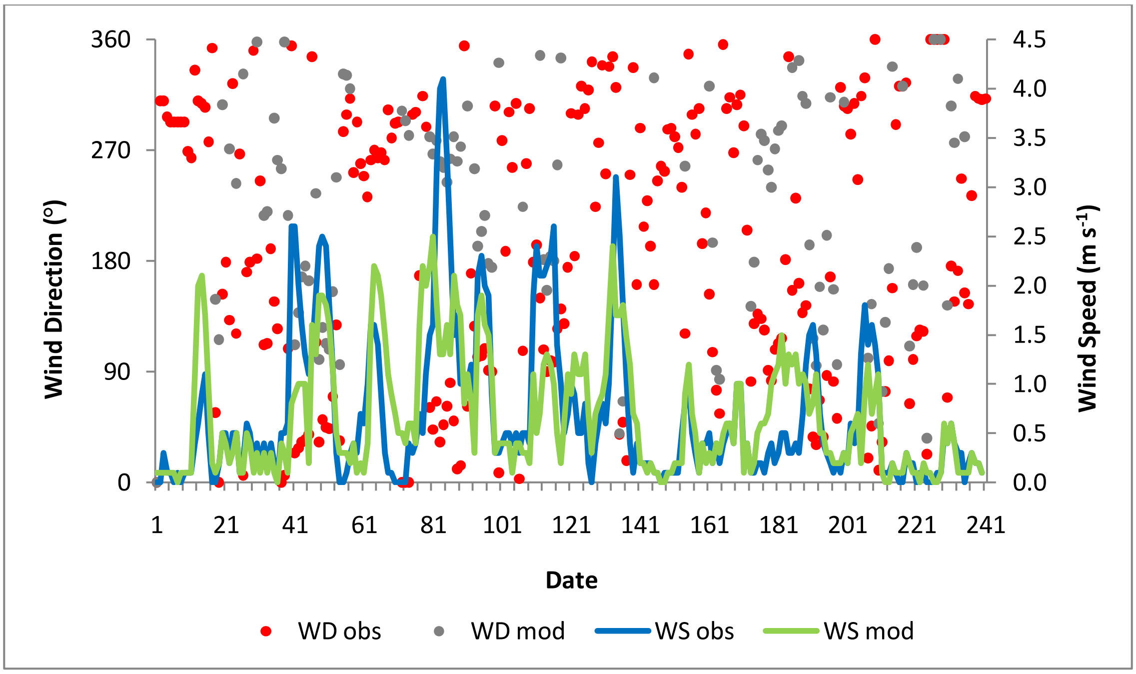

Figure 5.7 Time series of observed and modelled wind speed and wind direction for 21 – 30 June 2008 in Alexandra. Observational data are from the ORC monitoring site.

Modelled air temperature follows the same general trend as observed air temperature over this 10 day case study (Figure 5.6), with maximum temperatures matching very closely. Some error occurred in minimum temperatures, with modelled temperatures sometimes higher and sometimes lower than those observed. Nonetheless, the IOA and the RMSE suggest that the agreement is good and the error is small (Table 5.5). There was a gap of 19 hours in the ORC temperature data on 24 and 25 June of this case study, so a linear regression was performed using the remaining ORC temperature data and temperature data from West's (2008) AWS 2 km away. The resulting regression equation was used to calculate the values for the missing hours (see Appendix B for details).

Given that data assimilation for wind speed was used, modelled wind speeds for this case study also match observed wind speeds well, as expected. The greatest error lies in TAPM sometimes failing to reach the same maximum as that observed (Figure 5.7). Wind speeds are low over much of the study period, with the higher wind speeds between 22 and 26 June coinciding with the stronger south-westerly flow occurring at this time (Figure 5.5). However, wind direction for this case study is very changeable, with no evidence of a dominant wind direction. This supports the theory that the wintertime wind regime in Alexandra is driven by surface energetics; if drainage winds

Table 5.5 Summary and validation statistics for observed and modelled temperature, wind speed, and PM10 for 21 – 30 June 2008 in Alexandra. Observational data are from the ORC monitoring site.

Variable		Min	Max	Mean	St dev	IOA	RMSE
Temperature (°C)	Observed	-3.9	13.1	3.7	4.03	-	-
	Modelled	-8.0	13.7	4.4	3.88	0.72	3.98
Wind Speed (m s^{-1})	Observed	0.0	4.1	0.7	0.78	-	-
	Modelled	0.0	2.5	0.7	0.60	-	-
PM10 (µg m^{-3})	Observed	0.4	309.0	68.0	60.8	-	-
	Modelled	1.7	622.9	70.4	116.7	0.72	106.77

are converging in the town (which is situated in the lowest lying area of the basin) then it makes sense that the winds are coming from different directions.

Modelled PM10 concentrations follow observed trends moderately well, with peaks occurring at or around the same time (Figure 5.6). The large hourly spikes in PM10 mentioned in Section 5.2 can be seen on 27, 29 and 30 June. This results in a maximum modelled value double that of the observed, although the overall mean is very close, which means that modelled PM10 values were often under-predicted as well. The over-prediction of hourly PM10 by the model is likely to be the cause of the high RMSE, but the IOA is still good at 0.72 (Table 5.5).

To test how well TAPM was able to model the spatial distribution of PM10, a map was created to compare with the observational DustTrak data. Both maps show average values across the 10 day period, however, the DustTrak data are composed of instantaneous values between 0800 and 1130 hours and 1900 and 2230 hours which have then been averaged, whereas the model output consists of continuous hourly averages over the 10 days. It was expected that the modelled concentrations would be significantly lower than the DustTrak averages due to the fact that concentrations have been calculated for every hour rather than just for the morning and evening peaks. However, the modelled concentrations are fairly close in value to the measured concentrations. This may be because the lower daytime concentrations were balanced out by the higher night time concentrations, and the average of these does not affect the overall average for the study period. In any case, the maximum value calculated by TAPM was 70 µg m^{-3}, which is slightly less than the observed maximum which is

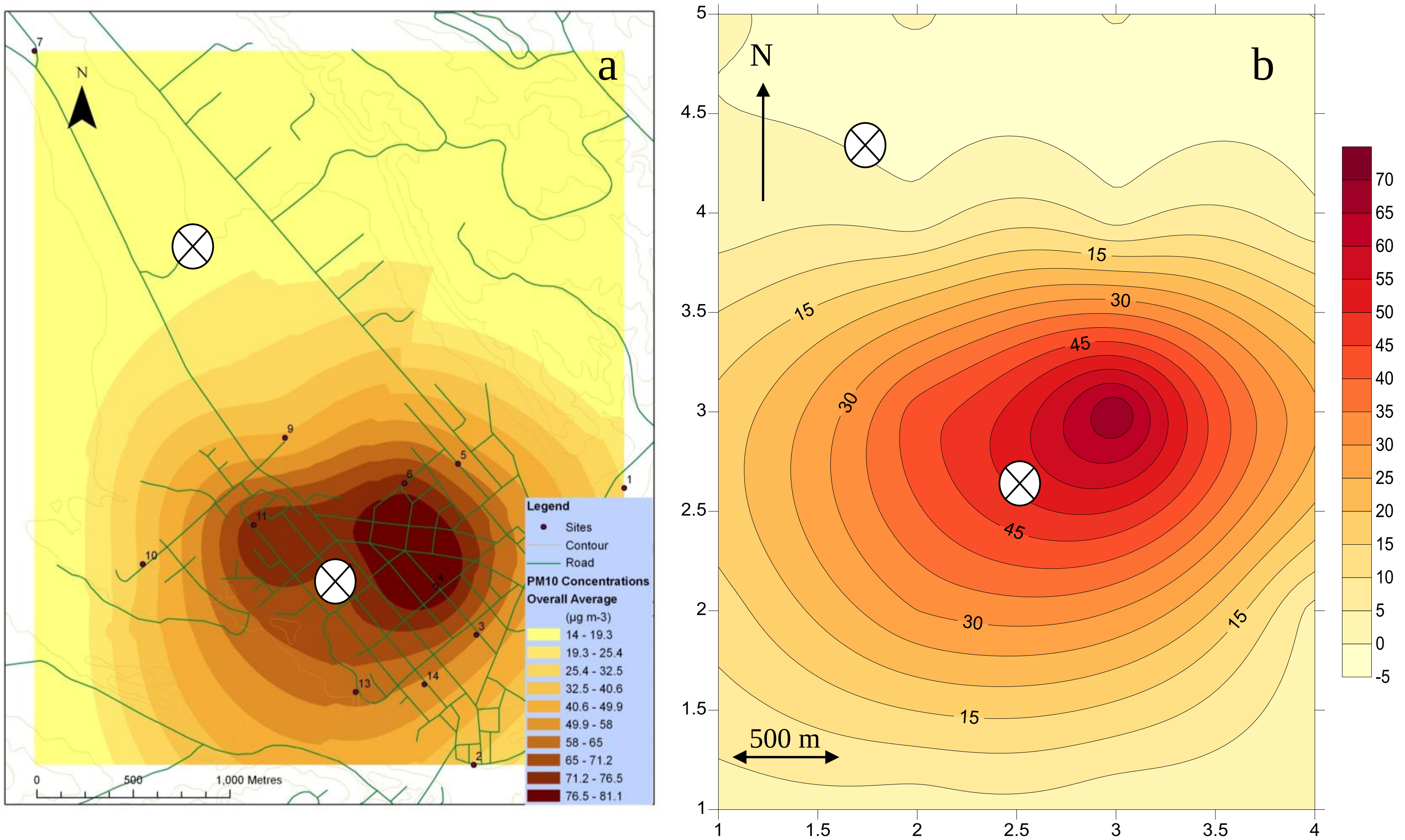

Figure 5.8 Measured PM10 concentrations (West, 2008) (a) versus modelled PM10 concentrations (b) for 21-30 June 2008 in Alexandra. The cross towards the north of each figure represents the location of West's (2008) AWS and the cross towards the south represents the location of the ORC monitoring site.

shown in Figure 5.8a as ranging between 76.5 and 81.1 μg m^{-3}. The positioning of the area of highest concentrations is also a very good match, which demonstrates that the model has performed well at simulating the spatial distribution of PM10 concentrations as well. Figure 5.8 also shows that, based on this case study, the ORC monitoring site is close to, but not within the area of worst air pollution, which is a requirement for air quality monitoring. For this case study, TAPM was initialised with an emissions profile that was homogenous across the town. Given the similarity of the observed and modelled spatial distribution of PM10, it appears, at least for Alexandra, that this simplified emissions profile with no spatial variability, is satisfactory.

5.6 Case Study Two: Alexandra, 23 August 2008

This case study examines a day where TAPM simulated the observational patterns in meteorology and air pollution concentrations particularly well. It was assumed that if the model was simulating meteorological and air pollution processes well at the grid point nearest the ORC monitoring site, then processes being modelled further afield (vertically and horizontally) could also be trusted. The synoptic situation on 23 August shows a series of cold fronts moving up the country at 0000 hours (Figure 5.9a). By midday however, these fronts have been interrupted by a ridge of high pressure that extends over New Zealand (Figure 5.9b), which is likely to result in calm, clear conditions.

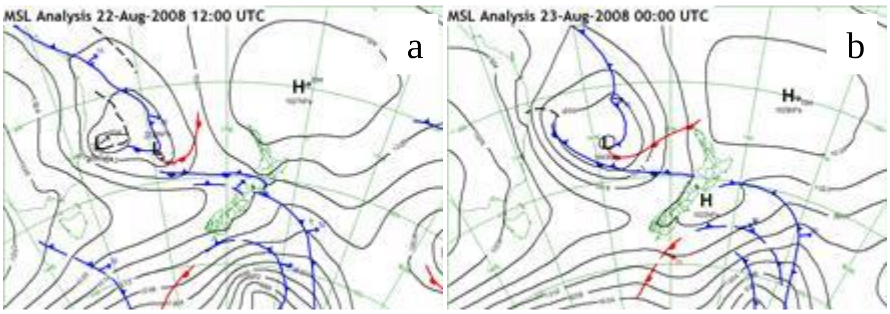

Figure 5.9 Synoptic situation for 23 August 2008 at 0000 hours (a) and 1200 hours (b) NZST.

Modelled air temperature follows the same trend as observed air temperature on 23 August but fails to cool sufficiently through the night time (Figure 5.10), resulting in a mean temperature almost four degrees higher than observed (Table 5.6). However, the IOA and RMSE indicate a good agreement and small error respectively, and the overestimation of air temperature by the model does not seem to adversely affect pollution concentrations.

As expected, due to data assimilation, wind speeds were also modelled well, except for a few hours in the afternoon when modelled wind speeds were lower than those

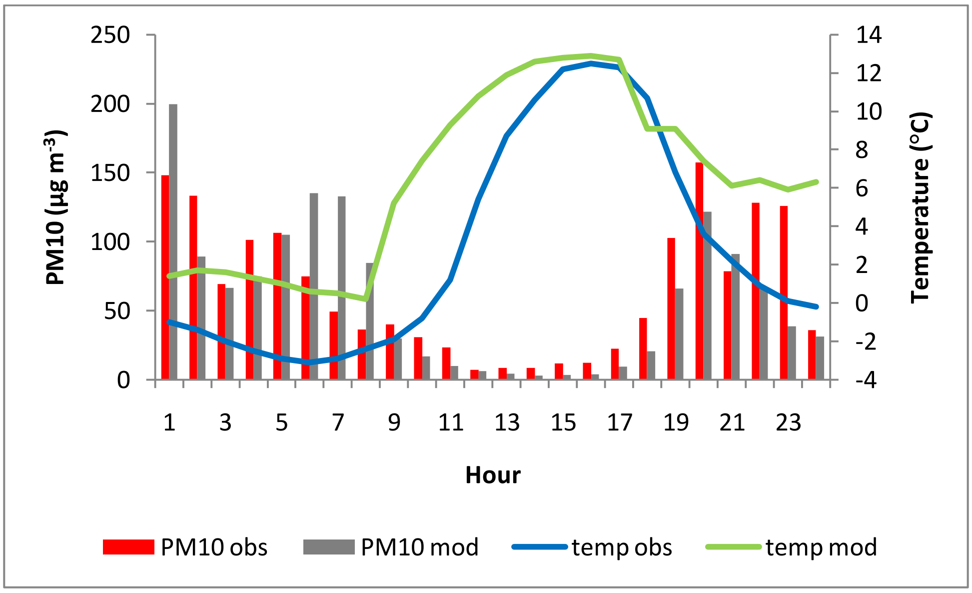

Figure 5.10 Time series of observed and modelled PM10 and observed and modelled temperature for 23 August 2008 in Alexandra. Observational data are from the ORC monitoring site.

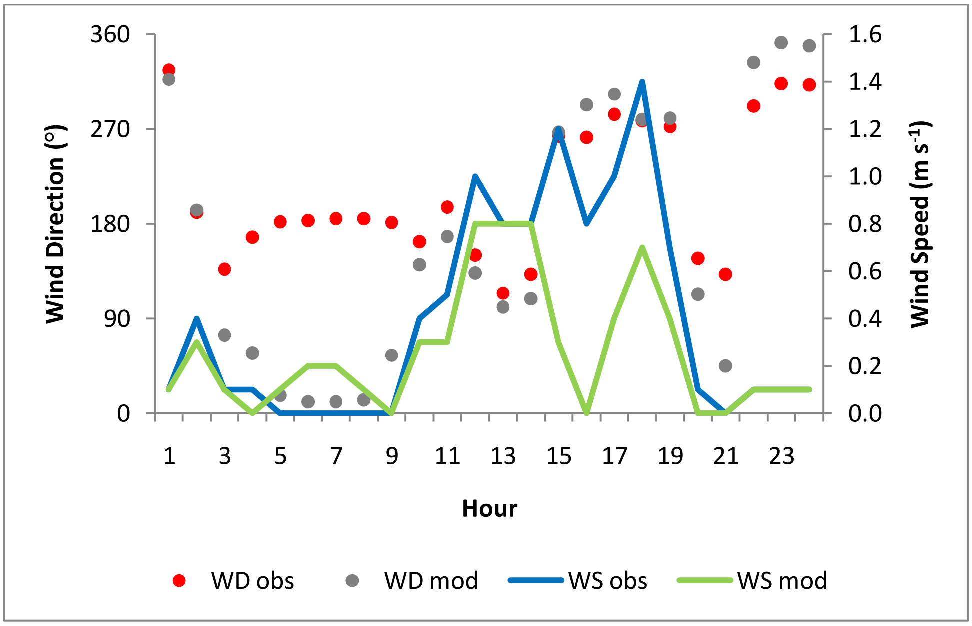

Figure 5.11 Time series of observed and modelled wind speed and wind direction for 23 August 2008 in Alexandra. Observational data are from the ORC monitoring site.

observed (Figure 5.11). Modelled wind direction matches observed wind direction fairly well on this day as well, except between 0400 and 0900 hours, but considering that wind speeds are extremely low during this time, this discrepancy is of little importance.

Modelled PM10 concentrations match observed concentrations well on this day with the modelled average for the day 6 µg m^{-3} less than that observed, and a good match visible even at an hourly scale (Figure 5.10). The model was able to capture an observed decrease in pollution levels at 0300 hours which may be a result of increased wind speeds at 0200 hours, which were likely to be drainage winds from the south

Table 5.6 Summary and validation statistics for observed and modelled temperature, wind speed, and PM10 for 23 August 2008 in Alexandra. Observational data are from the ORC monitoring site.

Variable		Min	Max	Mean	St dev	IOA	RMSE
Temperature (°C)	Observed	-3.1	12.5	2.8	5.60	-	-
	Modelled	0.2	12.9	6.4	4.52	0.84	4.38
Wind Speed (m s^{-1})	Observed	0.0	1.4	0.4	0.44	-	-
	Modelled	0.0	0.8	0.3	0.27	-	-
PM10 (µg m^{-3})	Observed	7.3	157.2	64.8	49.16	-	-
	Modelled	3.1	199.8	58.8	53.31	0.94	37.55

(Figure 5.11). This is reinforced by a high IOA between observed and modelled PM10 concentrations of 0.94 and a small RMSE (Table 5.6).

An advantage of numerical modelling is that the vertical structure of the atmosphere can be characterised. Figure 5.12 shows vertical profiles for temperature (a), wind speed (b) and wind direction (c) from 10 m above ground level to 1000 m above ground level at five key times throughout the day. When comparing the air temperature at different heights (and therefore different pressures) it is useful to use potential temperature rather than observed air temperature, as potential temperature assumes an arbitrary pressure value that remains constant with height (Oke, 1987). Potential temperature increases with height - which indicates that the atmosphere is stable - at all times throughout the day except 1200 hours, where a lapse profile can be seen from

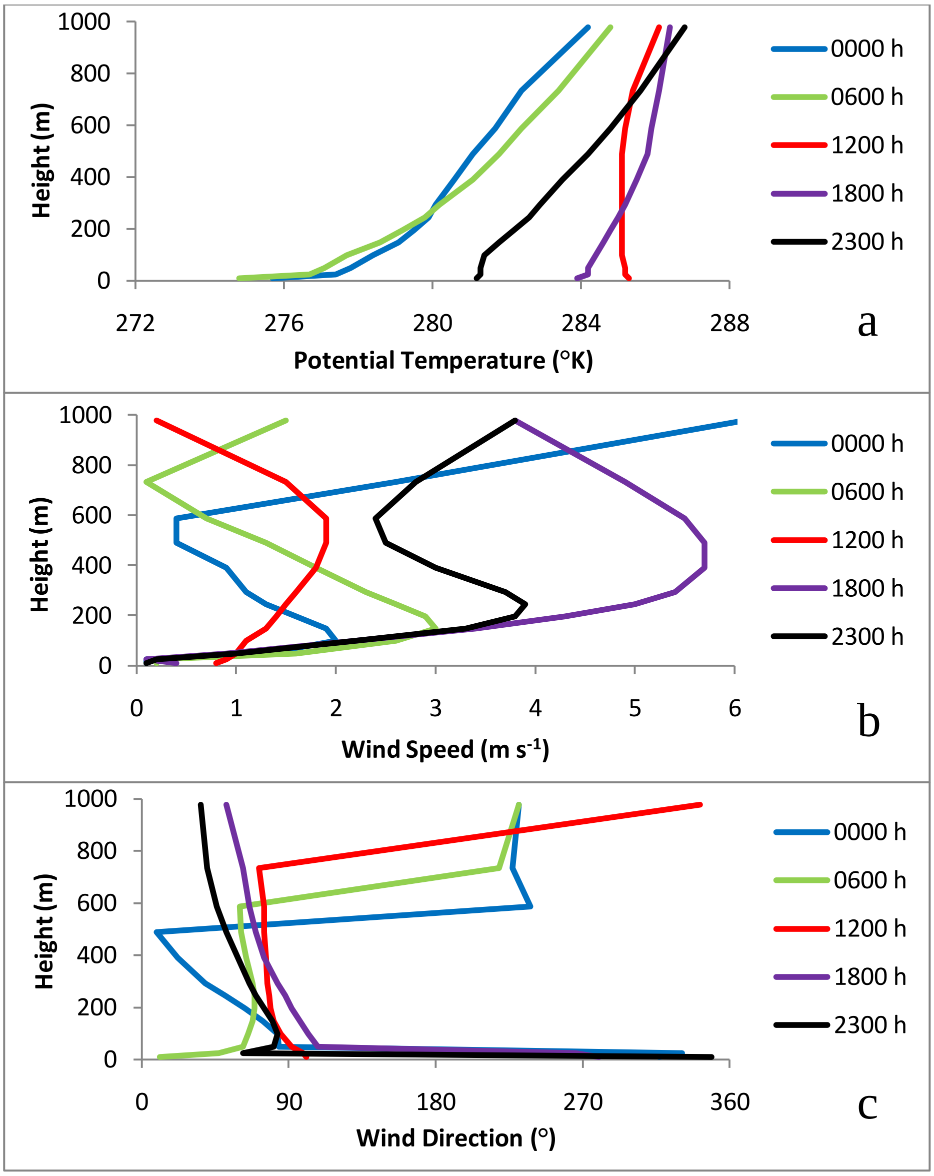

Figure 5.12 Vertical profiles of potential temperature (a), wind speed (b), and wind direction (c) on 23 August 2008 in Alexandra. Data have been extracted from the grid closest to the ORC monitoring site.

10 m up to 50 m, after which time temperature remains constant up to 600 m. Atmospheric stability is greatest at 0000 and 0600 hours between 10 m and 200 m above ground level (Figure 5.12a). At 0000 hours, potential temperature increases by 3.8 °K in the first 200 vertical metres, (or an increase from 2.6 to 6.4 °C). At 0600 hours, potential temperature increases by 4.4 °K, or from 1.7 to 6.1 °C for the same heights.

Except for at 1200 hours, wind speeds increase in the near-surface atmosphere, before decreasing and then increasing again with height. The height of maximum near surface

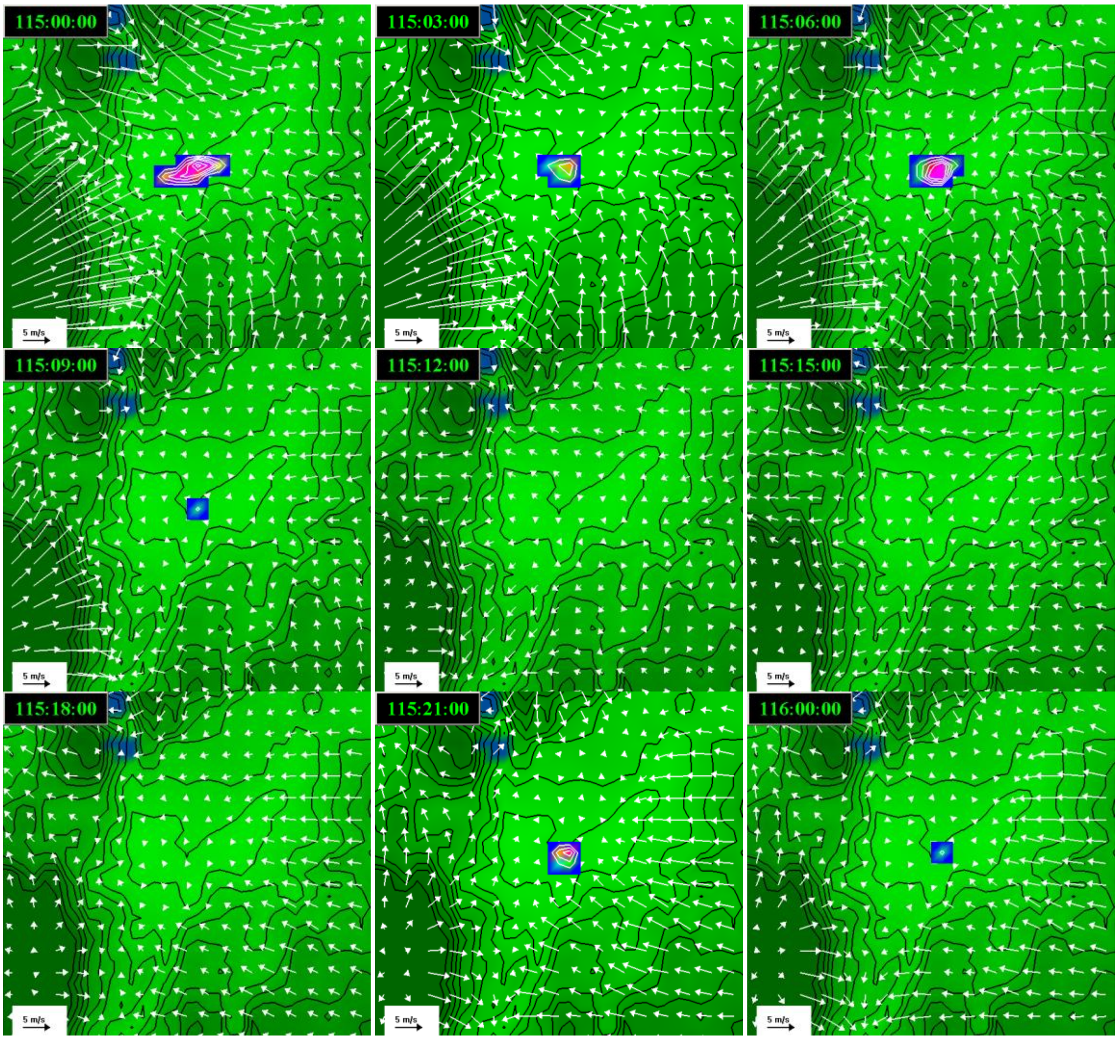

Figure 5.13 GIS visualisation from TAPM showing wind speed, wind direction, and pollution concentrations at three hour intervals on 23 August 2008 in Alexandra. Grid centre: 45°, 15' S, 169°, 22.5' E, grid resolution: 35 km^2.

wind speed increases throughout the day, from 150 m at 0000 hours to 400 m at 1800 hours. Wind direction is variable in the lower levels, but from 50 m to 500 m wind direction is from the east. However, wind direction switches to the west above 500 m at 0000 hours and 0600 hours which is likely due to the synoptic situation (Figure 5.9).

Another advantage of numerical modelling is that the air pollution meteorology can be examined spatially; this is not possible when only point source data are available. Figure 5.13 shows air pollution concentrations and the surface wind regime around Alexandra at three hour intervals for this case study day. At 0000 hours on 23 August TAPM has simulated drainage winds from the surrounding hills which are strongest from the north and south-west. All drainage winds slow and converge at the bottom of the basin. The drainage winds persist through the night but weaken by 0900 hours. As shown in Figure 5.10, PM10 concentrations are reduced between midnight and 0300 hours, but increase again by 0600 hours. By midday no pollution is visible, and the down-slope drainage winds have reversed to up-slope winds on the hills to the north-west and south-west of Alexandra. The fact that TAPM was able to simulate basin winds, which are generated by surface heating and cooling, is likely to be facilitated by the calm synoptic situation observed on this day. By 1800 hours surface cooling has generated drainage winds again, and by 2100 hours pollution concentrations have built up.

An interesting point here is that both the drainage flows and the pollution concentrations at the end of this case study day (0000 hours on 24 August) are less than at the beginning of the day (0000 hours on 23 August). TAPM has predicted that air temperature remains at around 6 °C between 2100 hours and midnight, whereas observed temperatures decreased from 4 to 0 °C for the same time period. The simulation of higher air temperatures may be the reason for reduced drainage flows, as well as the reduction in pollution levels through convective mixing, which was contrary to observations (see Figure 5.10).

The decrease and subsequent increase in observed PM10 levels between 2000 and 2200 hours shown in Figure 5.10 was not captured by TAPM, but is something that was also observed on the diurnal ensemble of all high pollution days that were correctly forecast (Figure 4.6). This phenomenon will be discussed further in Chapter Six.

5.7 Case Study Three: Mosgiel, 23 August 2008

This day was chosen for a case study because spatial information on PM10 concentrations existed, by way of DustTrak sampling, which was conducted by the Otago Regional Council (2009b). Therefore, TAPM could be used to determine whether the modelled spatial concentrations were the same as the observed concentrations. As a coincidence, this case study, which is for Mosgiel, happens to fall on the same day as the previous one (for Alexandra), so the synoptic situation is the same (Figure 5.9).

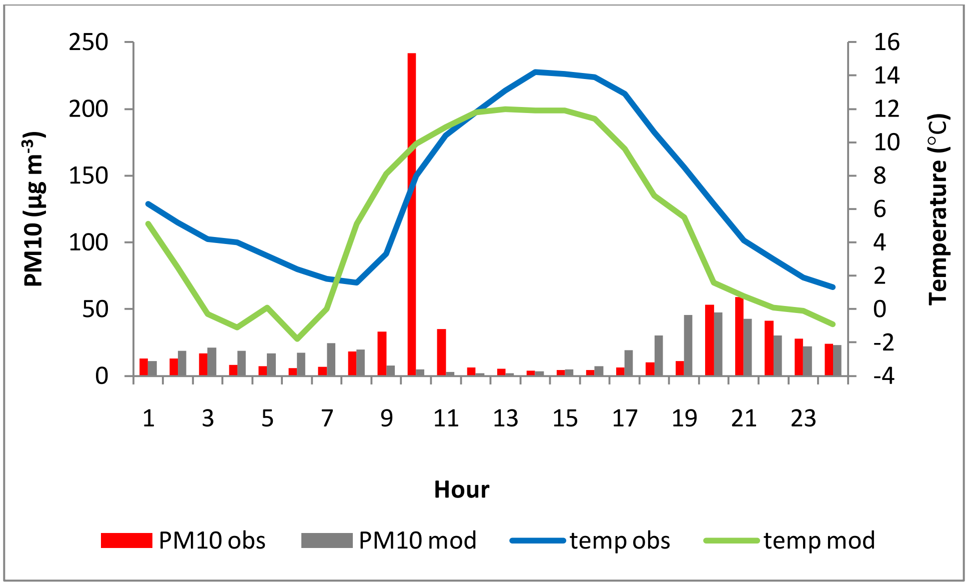

Figure 5.14 Time series of observed and modelled PM10 and observed and modelled temperature for 23 August 2008 in Mosgiel. Observational data are from the ORC monitoring site.

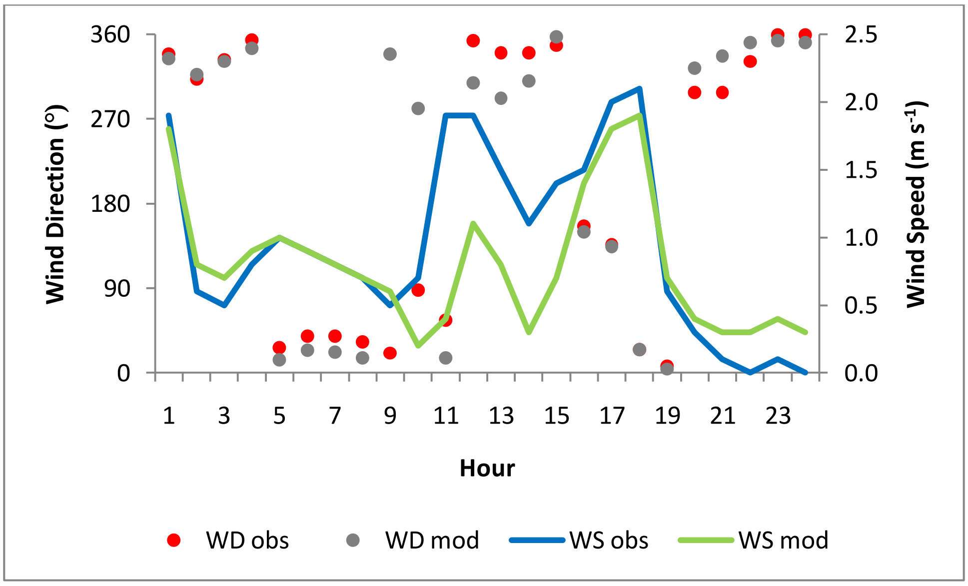

Figure 5.15 Time series of observed and modelled wind speed and observed and modelled wind direction for 23 August 2008 in Mosgiel. Observational data are from the ORC monitoring site.

The diurnal trend in air temperature has been modelled well on this day, although modelled temperatures are mostly lower than observed temperatures (Figure 5.14), and the mean temperature for the day is almost 2 °C less than the observed mean (Table 5.7). The match between observed and modelled wind speed and wind direction is also very good due to the effect of data assimilation (Figure 5.15).

Modelled PM10 concentrations match observed concentrations fairly well except for an unusual peak in observed concentrations that occurred at 1000 hours (Figure 5.14). This peak was likely due to a localised event rather than a reflection on ambient PM10 levels. It is highly unlikely that ambient levels increased and then decreased again that quickly as a result of emissions. During winter in 2008 a mineral loading operation was taking place in the vicinity of the monitoring site; therefore a possible explanation for this peak was that fine dust associated with the operation was picked up by the monitor (Mills, pers. comm. 2010). The monitoring site in Mosgiel is located in an industrial park and is classified as a 'peak' site rather than a 'neighbourhood' site due to the fact that it sometimes captures emissions close to the source of the monitor (Otago Regional Council, 2009b). The peak shown in Figure 5.14 is likely to be one of these occasions. Validation statistics were calculated both with and without the outlier, with a much improved IOA and RMSE once the 1000 hours concentration was removed (Table 5.7).

Table 5.7 Summary and validation statistics for observed and modelled temperature, wind speed, and PM10 for 23 August 2008 in Mosgiel. Observational data are from the ORC monitoring site.

Variable		Min	Max	Mean	St dev	IOA	RMSE
Temperature (°C)	Observed	1.3	14.2	6.9	4.58	-	-
	Modelled	-1.8	12.0	5.0	5.13	0.92	3.07
Wind Speed (m s^{-1})	Observed	0.0	2.1	1.0	0.67	-	-
	Modelled	0.2	1.9	0.8	0.50	-	-
PM10 (µg m^{-3})	Observed	3.7	241.7	27.3	48.32	-	-
Observed with outlier removed		3.7	59.0	18.03	16.19	-	-
	Modelled	2.2	47.7	18.5	13.52	0.35	50.33
IOA and RMSE once outlier has been removed						0.87	14.16

The vertical temperature profile for this case study day (Figure 5.16a) indicates that temperature increased with height throughout the day except for at 1200 hours. It seems likely that a weak gradient flow influenced the wind regime until around midday, after which time thermal winds had more influence. This would reduce the strength of the temperature inversion at 0000 hours and 0600 hours, and allow for a stronger inversion to have developed at 1800 hours and 2300 hours, as can be seen in Figure 5.16a. Temperature increased by 2.5 °K in the first 200 vertical metres at 1800 hours (an increase from 7.0 to 9.5 °C). At 2300 hours, temperature increased by 3.1 °K for the same heights, which equals an increase from 5.1 to 8.2 °C.

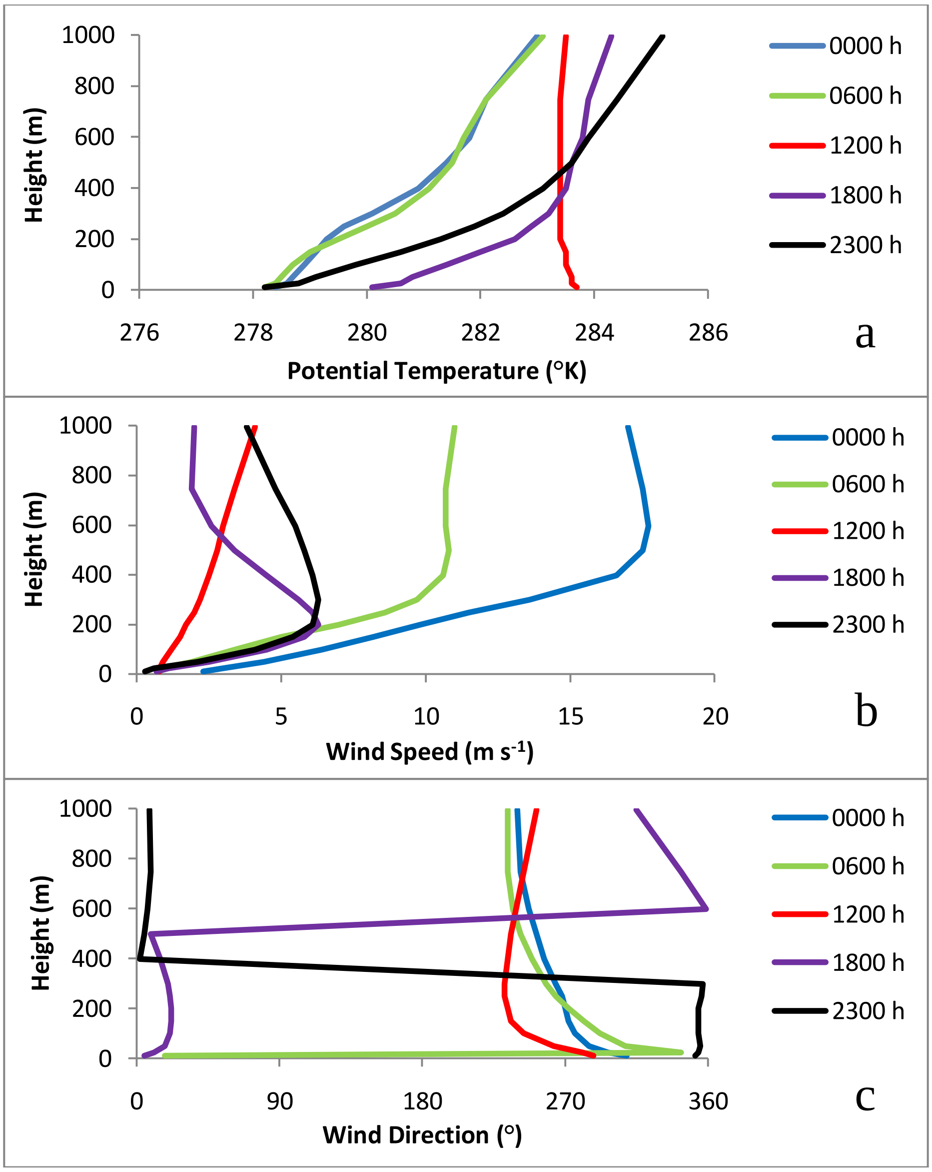

Figure 5.16 Vertical profiles of potential temperature (a), wind speed (b), and wind direction (c) on 23 August 2008 in Mosgiel. Data have been extracted from the grid closest to the ORC monitoring site.

The vertical wind profile (Figure 5.16b) shows that at 0000 hours and 0600 hours wind speeds increase with height until around 400 m, after which time they remain constant. At 1200 hours wind speed increases steadily with height, and at 1800 hours and 2300 hours wind speeds increase up to 200 m, after which time they decrease again. Wind direction (Figure 5.16c) is from the west from 0000 hours until 1200 hours, and then from the north at 1800 hours and 2300 hours.

As well as characterising meteorological processes through the vertical profile, TAPM was used to simulate these processes horizontally as well. Figure 5.17 shows modelled

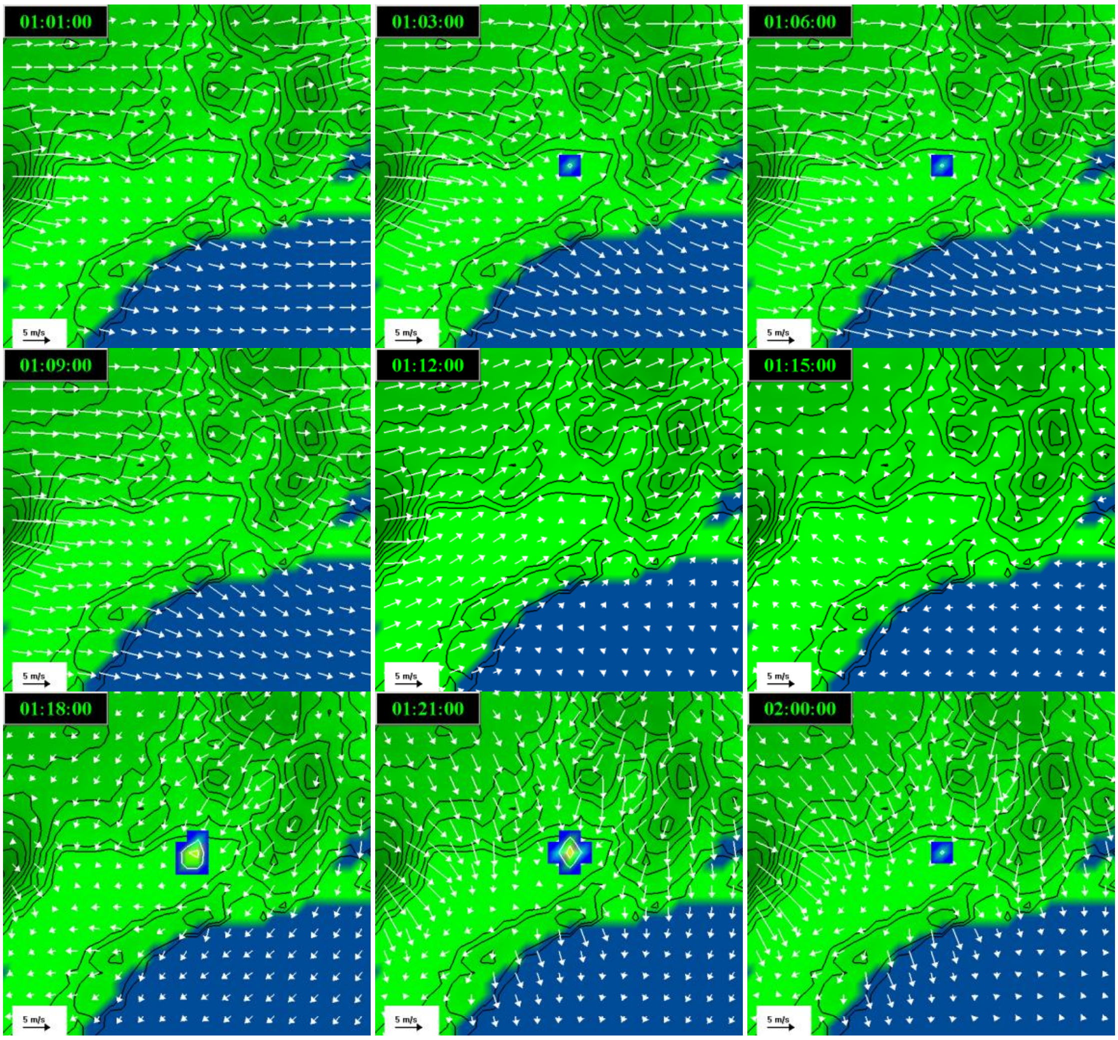

Figure 5.17 GIS visualisation from TAPM showing wind speed, wind direction, and pollution concentrations at three hour intervals on 23 August 2008 in Mosgiel. Grid centre: 45°, 53' S, 170°, 20' E, grid resolution: 35 km^2.

wind speed, wind direction, and pollution concentrations in Mosgiel at three hour intervals on 23 August 2008. TAPM has predicted that at 0100 hours the wind regime is predominantly from the west. These winds are likely to be a result of the synoptic situation rather than drainage winds (see Figure 5.9a). Wind speeds are still low around Mosgiel which is probably due to the sheltering effect of the hills. Figure 5.15 also shows wind speeds of around 2 m s^{-1} at midnight at the ORC monitoring site, which then ease over the next few hours.

The synoptic westerly flow dominates the wind regime around Mosgiel until 1500 hours on this day, after which time thermal winds become more dominant. This synoptic airflow initially prevents drainage winds from developing, and is also the likely reason that pollution concentrations are lower at 0300 and 0600 hours than they are at 1800 and 2100 hours; at which times the drainage winds from the hills to the north-west and north-east of Mosgiel have developed. Interestingly, Figure 5.17 does not show any drainage winds coming towards Mosgiel from the hills to the south, although some drainage winds are visible form these hills heading towards the coast. The absence of these drainage winds may be due to a lack of detail in the terrain file. Saddle Hill lies directly to the south of Mosgiel and has an elevation of 473 m, but TAPM’s terrain file has a height of only 111 m at this point, which may be an explanation for why these winds have not developed. This will be discussed further in Chapter Six.

A map of the modelled daily average spatial distribution of PM10 was also created for this case study day, and shows the highest concentrations occurring approximately 1 km to the south of the monitoring site (Figure 5.18b). Conversely, the highest observed concentrations are shown in Figure 5.17a to be approximately 1.5 km to the west of the monitoring site; thus, for this day, the ORC monitoring site is not located in the area of highest pollution. However, there are several explanations for the differences in both location and magnitude of pollution concentrations shown in Figure 5.18. Firstly, the DustTrak sampling took place between 2040 and 2300 hours which was the time of greatest emissions for the day (except for the spike at 1000 hours which was not a reflection of the ambient situation) (Figure 5.14), therefore it is expected that these instantaneous readings would be greater than the daily averaged values. Secondly, because the observed spatial distribution of pollution concentrations is based on only several hours of the day, the pattern shown in Figure 5.18a is not necessarily representative of the daily average pattern. Thirdly, it can be assumed that the spatial variability of PM10 concentrations shown in Figure 5.18a is likely to be a reflection of variation in emissions; this is something that TAPM could not have simulated given that there was no spatial variability in the area source file that was used.

In actuality, the eastern half of Mosgiel is dominated by open park areas, schools and retirement villages, whereas the western half is dominated by residential areas, with greatest housing density in the north-west (Otago Regional Council, 2009b). Based on this information, it makes sense that the highest concentrations occurred in the high density residential area, especially since the data were collected in the evening when people tend to be at home.

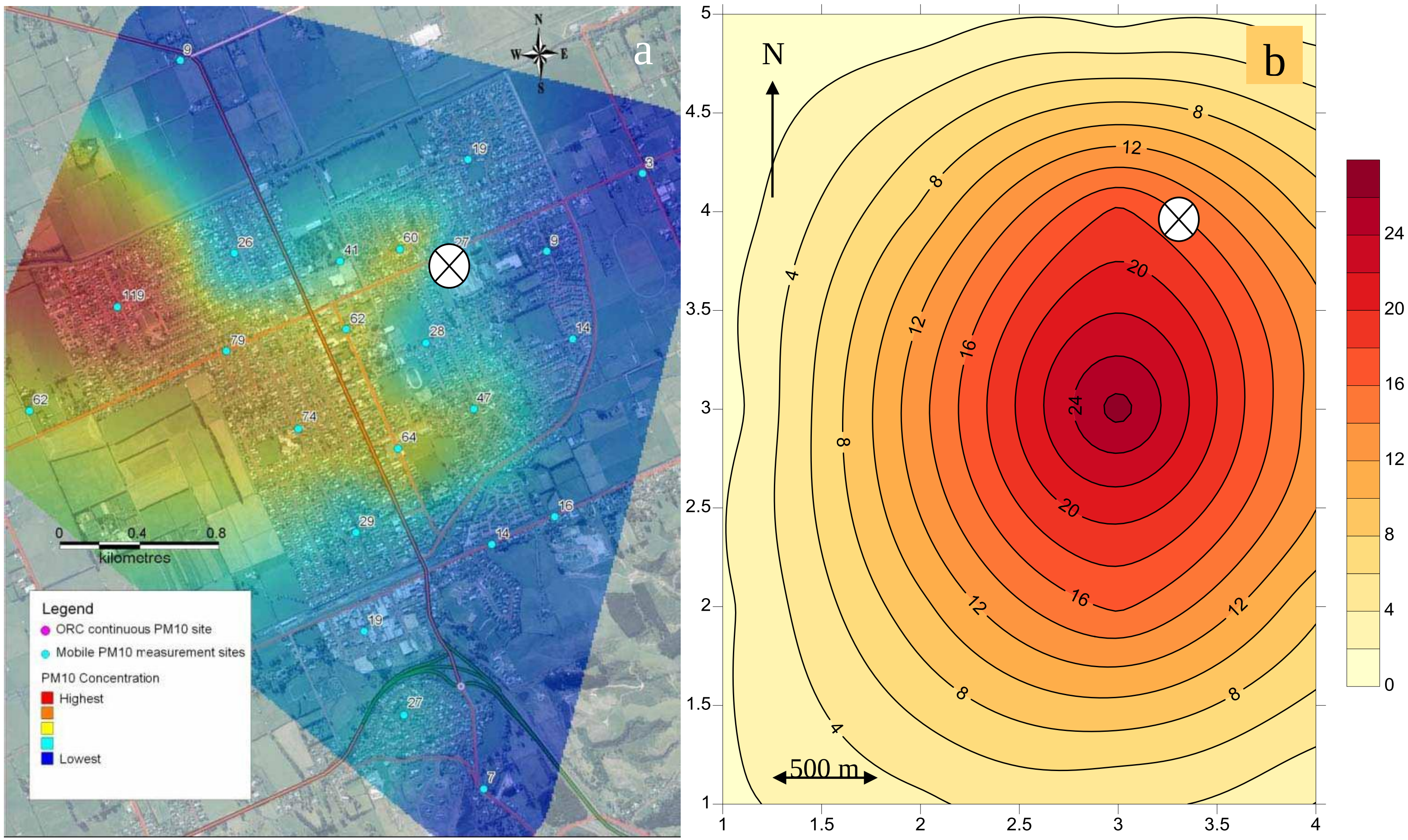

Figure 5.18 Measured PM10 concentrations between 2040 and 2300 hours (ORC, 2009b) (a) versus daily averaged modelled PM10 concentrations (b) for 23 August 2008 in Mosgiel. The cross represents the location of the ORC monitoring site.

During the time that the DustTrak readings were taken, it was noted that there was a light north-east wind in operation, which may have contributed to the high readings in the west, as polluted air was being transported from east to west across the town. Figure 5.17 also shows north-east winds occurring at 2100 hours and midnight, which are drainage winds from the hills to the north and east of the town. This has implications for the location of the monitoring site, which is situated in the north-east quarter of the town. It is expected that these drainage winds will develop under clear, calm conditions, thus transporting polluted air away from the monitor and resulting in lower night time values being recorded. This may mean that the monitoring site is not within the area of worst air pollution, which is a requirement for air quality monitoring.

5.8 Summary

TAPM was used to model meteorological conditions and PM10 concentrations from 1 May – 31 August 2008 in both Alexandra and Mosgiel. Air temperature was over-predicted slightly in Alexandra and under-predicted slightly in Mosgiel, although the match was generally good. The use of data assimilation resulted in a good match between modelled and observed wind speeds, although wind speeds in Mosgiel were still over-predicted by TAPM. Pollution concentrations were modelled more accurately in Alexandra than in Mosgiel, with a greater number of breach days correctly forecast.

Case studies have shown that TAPM is a valuable tool for simulating atmospheric processes, both horizontally and vertically, and can also shed light on the spatial distribution of PM10 concentrations. Case Study One showed a close match between modelled average PM10 concentrations and observed concentrations for a 10 day period, in terms of both the location and magnitude of highest concentrations. Case Study Two showed that TAPM was able to simulate a temperature inversion and diurnally switching basin winds over the course of a single day. Case Study Three showed that TAPM was able to simulate drainage winds and daily average pollution concentrations over the course of a day, although it was difficult to compare the latter with observational spatial concentrations due to the temporal difference between the two. Case Study Three also highlighted the limiting effect of an emissions profile that lacks spatial variability.

6

Discussion

6.1 Introduction

In this chapter the findings from the previous two chapters will be discussed in regard to the research aims of this study. The model performance will be summarised and the limitations of this research presented. This will be followed by a discussion on the implications of the findings of this research in relation to achieving National Environmental Standards (NES) for air quality in each town. Finally, alternative measures for reducing atmospheric pollution will be offered.

6.2 Summary of Model Performance

Overall, with the model set-up that was used, TAPM was able to reproduce the meteorological conditions of each town quite well. In particular, the thermal flows, which are a characteristic of the air pollution meteorology of each town, were well captured. In Alexandra, TAPM simulated diurnally reversing basin winds, which were generated by surface heating and cooling. In Mosgiel, TAPM simulated drainage winds from the hills to the north-east of the town, which were a result of nocturnal cooling, and in line with observations. The remainder of this section will discuss in detail the model performance in regard to the parameters that were selected.

6.2.1 Air Temperature

Over the modelling period, which ran from 1 May – 31 August 2008, mean modelled air temperature in Alexandra was 5.8 °C, which was 1.5 °C higher than the observed mean of 4.3 °C. In Mosgiel, the mean modelled air temperature of 5.9 °C was 0.4 °C lower than the observed mean of 6.3 °C. The magnitude of these differences in air temperature is in line with other TAPM modelling studies (e.g. Hurley et al., 2003; Zawar-Reza et al., 2005b; Gimson et al., 2007). It is likely that the reason modelled air temperature was higher than that observed in Alexandra, and lower than that observed in Mosgiel, is related to soil moisture content. Similar to the properties of a body of water, the moisture content in soil affects the rate at which it heats and cools, which in turn affects the heating and cooling of the air above the surface (Oke, 1987; Sturman and Tapper, 2006). If the soil moisture content is high, air temperature is reduced by day through evaporative cooling, whilst at night nocturnal cooling is reduced due to higher thermal admittance of the surface (although this process is of less importance, especially in winter when daytime heating is reduced). Conversely, if the soil moisture content is low, evaporative cooling is reduced, which leads to higher air temperatures by day, and, given lower thermal admittance, greater surface cooling resulting in lower temperatures at night.

For Alexandra, the modelled minimum air temperature was lower, and the maximum was higher than that observed, with the greatest error occurring in an over-prediction of daytime maximum temperatures (Table 5.1 and Figure 5.1a), which indicates that the soil moisture content chosen for the model set-up may have been too low. Therefore, increasing the soil moisture content may reduce the mean air temperature, resulting in a better match between modelled and observed air temperatures. In a study of TAPM's ability to reproduce meteorological processes in Christchurch, Hirdman (2006) found that increasing the soil moisture content resulted in a better agreement between observed and modelled air temperatures during the day, but also lead to a worse agreement at night, due to increased thermal admittance. For Mosgiel, the minimum and maximum modelled air temperatures were both lower than those observed, with the greatest error occurring in an over-prediction of night time minimum temperatures (Figure 5.4a). Therefore, reducing the soil moisture content in the model set-up should lead to an increase in mean air temperatures at this location.

Deep soil temperature and sea surface temperature were set at 6.4 °C in both towns, which is a reduction of 5 °C from the default setting. These two parameters can be altered individually, but it was found that reducing them both by the same magnitude gave the best result in terms of bringing modelled temperatures closer to observed temperatures. This is also in line with the findings of Hirdman (2006). Despite the fact that neither of the two towns are coastal, the sea surface temperature is still important. This is because the outermost grid contained most of the South Island as well as the Pacific Ocean to the east and the Tasman Sea to the west. Because New Zealand is a relatively small land mass surrounded by water, the thermal characteristics over water will have an effect on the thermal characteristics over land. Also, considering that deep soil temperature should be approximately the same as mean air temperature, the chosen deep soil temperature of 6.4 °C seems more appropriate than the default setting of 11.4 °C. It is important to note that TAPM was developed in Australia, and because of this the default settings are probably more appropriate for the Australian environment. Therefore, it seems reasonable to alter these settings so that they match the chosen study area as closely as possible.

Temperature Inversions

This research has shown, through use of the numerical model TAPM, that under calm, clear conditions temperature inversions are occurring in each town. For example, Case Study Two (Section 5.6) showed that temperature increased by as much as 4.4 °C between 10 m and 200 m above ground level in Alexandra. Tate and Spronken-Smith (2008) suggested that temperature inversions were a causative factor leading to high air pollution levels in Alexandra. Following this, West (2008) and the Otago Regional Council (2009a) determined, through the installation of temperature sensors on a hillside to the south of Alexandra, that temperature inversions were indeed occurring, with a temperature increase of approximately 2 °C between the monitoring site on the basin floor and the highest temperature sensor. Because the highest sensor was only 80 m above the basin floor, it is likely that temperature continued to increase above this height, resulting in an even stronger inversion than that measured (West, 2008).

Case Study Three (Section 5.7) showed that temperature increased by as much as 3.1 °C between 10 m and 200 m above ground level in Mosgiel. Mulliner et al. (2007) also suggested that temperature inversions occur in Mosgiel through radiative cooling. In another study in Mosgiel, TAPM was used to simulate a high pollution episode occurring from 15 -18 May 2008. At the time of the highest hourly air pollution concentrations during the study, TAPM simulated a temperature inversion, with temperature increasing by 3 °C through the vertical profile (Reese, 2009).

In a recent study in Milton, Otago (50 km south of Dunedin), TAPM was also used to model meteorology and air pollution. It was found that during high pollution events a temperature inversion developed to a height of 150 m, and within this was a strongly stable layer to a height of 25 m (Broadbent et al., 2010).

6.2.2 Wind Speed and Wind Direction

Data assimilation files for wind speed and direction were used in this study. When these files were not included wind speeds were over-predicted, which lead to pollution concentrations being under-predicted. The over-prediction of wind speeds during calm conditions has been encountered in other modelling studies using TAPM (Gimson et al., 2007; Zawar-Reza et al., 2003). Ideally, the observational wind speed and wind direction data should be sourced from a location outside the innermost grid, so that validation statistics such as the index of agreement (IOA) and root mean square error (RMSE) can be calculated on the data extracted from the grid point of interest within the innermost grid. However, because Alexandra is situated in a basin completely surrounded by hills, and Mosgiel is situated on the Taieri Plains which are surrounded by hills on three sides, wind data sourced from outside the study areas may not have helped to characterise the wind regime within the study area.

Observed mean winds were generally very low for each town (0.6 m s^{-1} for Alexandra and 0.8 m s^{-1} for Mosgiel) during the modelling period, and these winds were often a result of surface energetics rather than the synoptic situation. Therefore, in order to simulate this wind regime effectively, it was required that observational data were sourced from within the study area. TAPM simulated wind speed and wind direction at ground level, and through the vertical profile to a maximum height of 1500 m above ground level. However, because there was no observational wind data through the vertical profile, the modelled vertical could not be validated and should therefore be treated with some caution.

Drainage Flows

Drainage flows are important in characterising the air pollution meteorology within an airshed. This is because they not only transport cold air to lower elevations, which facilitates the formation of temperature inversions; but they can also transport polluted air, thus affecting the spatial distribution of air pollution concentrations. As shown in Figures 4.5 and 4.9, both Alexandra and Mosgiel experience a wind regime that lacks a dominant wind direction, both annually and during the winter months alone (although some channelling of synoptic winds does occur in Mosgiel). This indicates that winds are driven by differential surface heating and cooling producing thermal winds, rather than the over-riding synoptic situation. Therefore, thermal winds are an important characteristic in the air pollution meteorology of Alexandra and Mosgiel, due to the effect they have on inhibiting the dispersion of pollutants. TAPM was able to simulate these drainage flows well, which resulted in the formation of concentric patterns of modelled air pollution concentrations, with the highest build-up of air pollution occurring at the point where drainage flows slowed and converged (Figures 5.8 and 5.17).

In Alexandra, the constrained topography, coupled with the lower air temperatures experienced there, is a likely cause of the high air pollution concentrations, despite a relatively small population. Temperature inversions are enhanced in basins as cold air drains off the surrounding hills and forms a cold air pool. In wintertime, this cold air pool can persist for days as daytime surface heating does not produce enough convection to break up the inversion (Whiteman, 2000). This likely happens in Alexandra and means that each day’s emissions will be added to the last, as the pollution cannot escape the basin.

The problem is not as severe in Mosgiel, as the town is bounded by hills on three sides, but is exposed to winds from the south-west. Despite this, drainage winds are still an important feature in Mosgiel, as they form under calm conditions when there would be no south-west winds. However, the unconstrained topography to the south-west of Mosgiel plays a key role in the air pollution meteorology of this town, as it means drainage winds from the north-west are not met by opposing south-west drainage winds, as is the case in Alexandra. Thus, air pollution can be carried away from the town, resulting in lower concentrations.

6.2.3 PM10 Concentrations

Overall, PM10 concentrations were over-predicted by 41% in Alexandra and 48% in Mosgiel. Other modelling studies have resulted in both over-prediction (Hurley et al., 2008; Conway et al., 2007) and under-prediction (Hurley et al., 2003; Broadbent et al., 2010) of PM10 concentrations, although the error between observed and modelled concentrations was generally less for these studies. Despite this, TAPM correctly forecast 66% of the time in Alexandra and 71% of the time in Mosgiel in terms of breaches and non-breaches.

The under-lying cause for the over-prediction in pollution concentrations was a tendency for TAPM to simulate large spikes in hourly concentrations between 1900 and 2100 hours. This pattern was observed by Conway (2006) as well, with TAPM simulating a peak in PM10 concentrations almost 700 µg m^{-3} greater than the observed concentrations. Conway (2006) suggested that the cause of this peak was due to an inaccuracy in the emissions data that were used.

Aside from inaccurate emissions data, another possible explanation for the over-estimated modelled peak in evening PM10 concentrations is an over-prediction of the atmospheric stability at this time. An example of these evening peaks in PM10 concentrations can be seen in Figure 5.6 (Case Study One). At 2100 hours on 29 June the modelled hourly concentration for PM10 was 590 µg m^{-3}, whereas the observed hourly concentration was 148 µg m^{-3}. At this time, TAPM simulated an increase in potential temperature of 8 °K between 9.8 m and 1467 m above ground level. Similarly, the following day at 2000 hours the modelled concentration was 541 µg m^{-3}, compared to an observed concentration of 122 µg m^{-3}. This time TAPM simulated an increase in potential temperature of 12 °K for the same heights. As there is no observational vertical temperature data to compare TAPM's predictions with, it is difficult to comment on these figures with any level of certainty. However, it seems likely that TAPM has over-predicted the degree of atmospheric stability, which has contributed, at least in part, to the over-prediction of PM10 concentrations. It is not known what the cause of the over-prediction in atmospheric stability was, but it may link back to soil moisture. If the soil moisture content defined in the model set-up was too low, the Earth's surface would cool rapidly after sunset, thus cooling the air above the surface as well. If this is the case, fine tuning the soil moisture content in the initial stages of the model set-up may improve both modelled pollution concentrations and modelled air temperatures. This may improve modelled pollution concentrations in Alexandra, but is likely to worsen them in Mosgiel, as it has already been suggested that soil moisture content was set too high.

6.2.4 Synoptic Considerations

Through analysing the model output, it was observed that the model performed best during anticyclonic synoptic conditions, and was overly influenced by cyclonic conditions or the passage of fronts which interrupted surface energetics such as basin winds and temperature inversions. However, at least in Alexandra, West (2008) and Tate and Spronken-Smith (2008), noted that the meteorology can follow cycles akin to those experienced under anticyclonic conditions, when in actuality a frontal system may be passing over, due to the fact that decoupling occurs between the atmosphere in the basin and the overlying synoptic situation (Figure 6.1). Therefore, the accuracy of

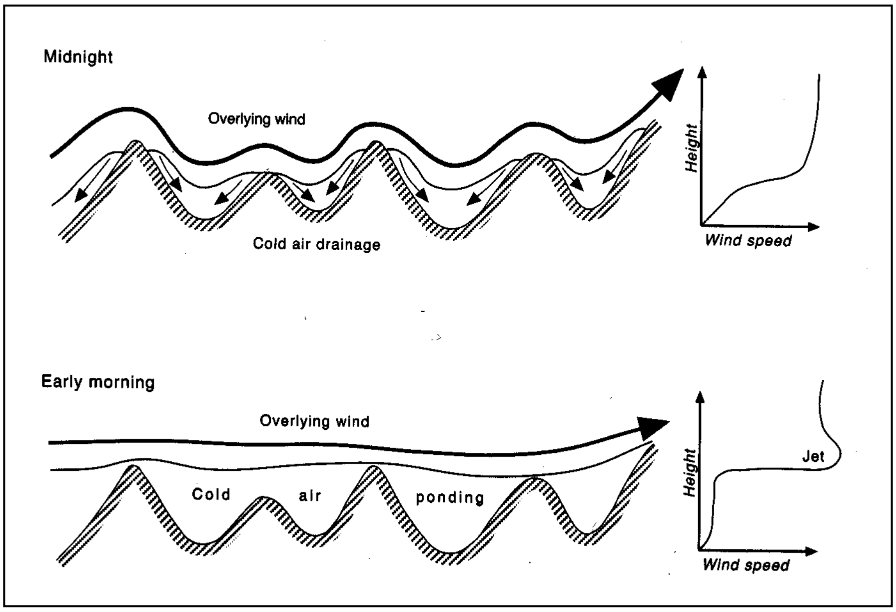

Figure 6.1 Decoupling of the atmosphere within a basin from the over-riding synoptic situation due to cold air drainage. Source: Sturman & Tapper, 2006, p 317.

the model may be compromised when simulating meteorology and air pollution concentrations during periods of atmospheric instability, as these processes over-influence the meteorological and air pollution patterns occurring within the basin. For example, in Alexandra, the highest daily average PM10 concentration of 150 µg m^{-3} occurred on a day when a cold front was moving across the country. West (2008) observed that a temperature inversion was in place in the basin throughout the day, and, unusually, was at its strongest at 1500 hours. However, TAPM predicted that potential air temperature remained constant up to 300 m above ground level at 1500 hours. TAPM also over-predicted daily air temperature by 5.8 °C and under-predicted daily PM10 by 86 µg m^{-3} on this day. The changes in wind speed and wind direction shown at the higher vertical levels in Figure 5.12 may also be an indication of the height to which decoupling occurs.

6.3 Limitations

6.3.1 Observational Meteorological Data

As stated in Section 3.4.1, wind speed and wind direction should be measured at a height of 10 m above ground level and the monitoring site should be clear of obstructions such as buildings and trees. However, the observational wind data used in this study were measured at 3 m above ground level and both sites were in reasonably close proximity to buildings (see Figure 3.4). Due to these factors, the observational wind speed data are likely to be slightly under-represented. As the modelled wind speed and direction are given at a height of 10 m above ground level, it makes sense that modelled wind speeds were often slightly higher than observed wind speeds, despite the assimilation of observed wind data. The heights of the instruments are included in the data assimilation file, which probably reduced the error between the two, but the modelled and observed winds were still being compared after being taken from two different heights, which is less than ideal.

One of the main contributions of modelling is that meteorological processes can be characterised through the vertical profile. However, these data cannot be validated if there are no observed vertical data, and should therefore be treated with some caution. Ideally, the modelled vertical data would be validated against measured radiosonde data to determine whether processes such as temperature inversions were being modelled accurately. There are no existing vertical data for Alexandra or Mosgiel, which is also less than ideal.

6.3.2 Emissions Data

For this study, a single area source was used to represent the domestic emissions for each town, and a single point source was used to represent the industrial emissions for Mosgiel only. The total domestic emissions for an average winter day were calculated from DigiPoll telephone interviews (Wilton, 2006). As well as establishing the type and age of burner used, questions were asked regarding the number of pieces of wood (or coal) burnt on an average winter day. The weight of an average piece of wood was calculated to be 1.9 kg, but the species and moisture content were not established. The sample size of each town was 150, which represents 8% of the households in Alexandra, and 5.4% of the households in Mosgiel.

The figures calculated by Wilton (2006) appear to represent the daily average wintertime emissions for each town satisfactorily, although a possible cause of the over-estimation in modelled PM10 concentrations may have been due to the daily emissions value being too large. Also, the emissions data were lacking in spatial variability, which means that TAPM assumed the total emissions were spread evenly across the source area and could not consider spatial variation of emissions based on type of burner, type of fuel burnt, rate of fuel burnt, and housing density. In Alexandra, spatial patterns of modelled PM10 were similar to those observed, indicating that the assumption of homogeneity in emissions across the town was reasonable. However, this was not the case in Mosgiel. Case Study Three (Section 5.7) highlighted the importance that observational spatial variability of emissions likely had on the resulting modelled spatial variability of PM10 concentrations. In this case, the highest measured concentration in the north-west quarter of Mosgiel was likely due to higher housing density and therefore higher emissions, which was something that TAPM could not have reproduced, as this information was not given to the model. Therefore, determining the spatial variability of emissions is likely to improve the spatial variability of modelled concentrations.

Further to this, the daily average value for domestic wintertime emissions did not differentiate between weekdays and weekends, when in actuality it would be expected that the morning peak would occur later on weekends and total daily emissions would be greater due to the fact that people are more likely to be at home for a greater proportion of the day. This is in agreement with Zawar-Reza and Sturman (2008), who found that during a weekend in Christchurch the observed Saturday morning peak occurred later, the Saturday evening peak was higher and more sustained, and the Sunday morning peak was smaller (likely due to reduced transport and industrial PM10 emissions); all of which were not captured by TAPM due to the homogeneity of the emissions data across days of the week.

It was hoped that TAPM could be used to determine the required percentage reduction in emissions for Alexandra and Mosgiel so that the NES could be achieved. For a recent study in Milton, Otago, in which the winter of 2008 was modelled, Broadbent et al. (2010) found through numerical modelling using TAPM that a 50% reduction of both domestic and industrial emissions was required in this town for the NES to be adhered to. In Christchurch, a projected emissions rate for 2013 was used for a nine day period when TAPM performed particularly well, in order to determine if the predicted reductions would be sufficient for achieving the NES. Zawar-Reza and Sturman (2008) found that projected emissions for 2013 resulted in no breaches of the NES, based on the period modelled. However, daily values were as high as 45 $\mu g\ m^{-3}$, so with the addition of natural sources of PM10 such as wind blown dust or salt spray, or a period of strongly stable atmospheric conditions, a breach would be likely.

Because TAPM simulated large hourly peaks in modelled PM10 concentrations that were not observed, percentage reductions in emissions could not be calculated for either town. It is not known if these peaks were due to inaccuracies in the modelling of the meteorology, inaccuracies in the emissions data, or a combination of the two. However, Wilton (2006) suggests a reduction of 72%, or 328 kg per day in Alexandra, and 48%, or 275 kg per day in Mosgiel if the targets of the NES are to be reached.

6.3.3 Modelling Limitations

As already stated, selecting the correct parameters is an important part of the model set-up if processes are to be simulated accurately. In this research it was found that a soil moisture content of 0.15 $m^3 m^{-3}$ was slightly too low for Alexandra, whereas a soil moisture content of 0.3 $m^3 m^{-3}$ was slightly too high for Mosgiel. Fine tuning these parameters is time consuming considering that each parameter can be adjusted by a magnitude of 0.1; however it is a necessary process to go through as these parameters affect all other aspects of the model output. Similarly, in this research, deep soil temperature and sea surface temperature were both set at 6.4 °C, which Broadbent et al. (2010) also found to give the best result. However this setting was an arbitrary reduction of 5 °C from the default setting, and further fine tuning may have determined a more accurate value.

One of the parameters of the data assimilation file that was used is to select the number of vertical levels that the observational wind data is to have influence on. In this research, the first two vertical levels were chosen, which represents a height up to 25 m above ground level, and is in line with the model set-up of Broadbent et al. (2010) and Conway (2009). Hurley (2008b) states than care should be taken when selecting the number of vertical levels to include, as winds can vary significantly with height in the near surface atmosphere, but does not specify how many levels to include. It is likely that the number of levels to select will be site specific and will vary with location and time of year. Thus, care should be taken when interpreting the vertical data produced by TAPM when data assimilation is included. For example, if observed wind speeds have been assimilated in order to reduce modelled wind speeds, as is the case with this research, a sudden increase in modelled wind speeds between the top vertical level being influenced by the observed data and the subsequent level above that could be misinterpreted as an area of wind shear, when in actuality it is not. Because the observed wind data used in this research were taken at a height of 3 m, it may have been more appropriate for the data to only influence the first vertical level, which is to a height of 10 m above ground level.

Another modelling limitation encountered in this research is the accuracy of TAPM's terrain file. For example, the Clutha River flows past Alexandra (see Figure 3.5), but this is not visible in the GIS visualisation taken from the innermost grid, which has a resolution of 1 km^2 per grid cell (Figure 5.13). This may compromise the accuracy of the model simulations, such as the lack of drainage winds from Saddle Hill in Case Study Three (Section 5.7) which was likely due to the fact the height of this hill was underestimated by 362 m. A more detailed terrain file can be given to the model; however, this was not done for this research, but is recommended for future research using TAPM.

A final limiting factor encountered using TAPM was that simulations could not be run for a timeframe of less than one day (point source data were generated at hourly averages, but spatial data were automatically computed as daily averages for each grid cell). In regard to Case Study Three, the match between observed and modelled spatial PM10 concentrations was poor due to, at least in part, the discrepancy in timeframe between measured and modelled concentrations, with the measurements being comprised of instantaneous readings taken between 2040 and 2300 hours, whereas the modelled values were comprised of average concentrations over the whole day. If TAPM was able to simulate concentrations for the same timeframe as the DustTrak measurements, it would have been interesting to see how well the observed transport of pollutants from east to west was simulated.

6.4 Implications for Achieving the NES

Based on the number of exceedances of the NES that are currently occurring in each town, it appears that it would be almost impossible for the air quality targets to be reached by 2013. Even if the number of allowed exceedances is increased to three and the timeframe extended until 2020, which is likely to happen under the current National government (Ministry for the Environment, 2010), these targets are unlikely to be reached, especially in Alexandra. This means that no resource consents that allow emissions to the air can be granted.

However, for a town like Alexandra, which has little industrial activity and is mostly residential, reducing air pollution levels is still of paramount importance, purely because of its adverse effect on human health. As this research has shown, high levels of air pollution in Alexandra occur through atmospheric processes which trap the pollution near the surface; therefore, reducing emissions may only lead to limited improvement considering that daily averages can be as high as 150 µg m^{-3}, which is three times the legal limit. The NES states that from 2012 onwards newly installed wood burners in Airshed 1 towns (such as Alexandra) must emit no more than 0.7 grams of particulate per kilogram (g kg^{-1}) of dry wood burnt and have a thermal efficiency of at least 65%. It remains to be seen what effect this will have on air pollution levels, and the burning behaviour of individuals cannot easily be monitored or regulated. For Alexandra, it appears that the only way to improve air quality is to phase out domestic fuel burners entirely. However, doing this would increase reliance on electricity, which may cause a new problem in the event of a power cut during a period of low temperatures.

Fewer breaches of the NES occur in Mosgiel, and daily levels are lower, so reducing emissions in this town may make reaching air quality targets more achievable. From 2012 onwards, newly installed wood burners will not be allowed to emit more than 1.5 g kg^{-1} and must have a thermal efficiency of at least 65%.

Based on Figure 5.8, Figure 5.17, the Alexandra DustTrak measurements (West, 2008) and the Mosgiel DustTrak measurements (Otago Regional Council, 2009b) it appears that neither ORC monitoring site is located in the area of worst air quality, which means that actual concentrations may be even higher than those measured. For Alexandra (based on the findings of Case Study One), maximum PM10 concentrations may be 20 µg m^{-3} higher than what is currently being measured, with the area of worst air quality lying 500 m to the north-east of the current monitoring site. In Mosgiel, based on the reduced evening peak shown in Figure 4.6b and the higher concentrations to the west and south of the monitoring site that were recorded during evening DustTrak sampling (Otago Regional Council, 2009a), it appears that the evening peak in emissions is not being well captured by the monitor. This is likely to be due to the transportation of polluted air away from the monitor as a result of drainage winds from the north-east. As the greatest amounts of emissions are released during the evening, it is possible that under calm conditions PM10 levels are considerably higher in Mosgiel than the values being recorded by the monitor.

It has also been suggested that the bimodal peak in evening emissions on high pollution days in Alexandra (Figure 4.6a) may be a result of clean air being moved across the monitor (Conway, 2009). If so, it is likely that the clean air is being transported by drainage winds from the west or south of the monitoring site. Figure 5.13 shows light drainage winds from the hills to the south-west of Alexandra at 2100 hours (which is when the evening dip occurs), but it is difficult to determine with any certainty whether or not this is the sole cause of the bimodal evening peak.

Earlier research, by Tate and Spronken-Smith (2008), put forth several other possibilities, including the transport of polluted air from Clyde (9 km to the north-west of Alexandra), thus increasing pollution levels in Alexandra at 2200 and 2300 hours; cold air avalanching down the Clutha Gorge, thus reducing pollution levels from 1900 to 2100 hours, after which time they would build up again; or the patterns of domestic burning behaviour, such as the timing and frequency that fuel is loaded into the burners. However, Conway (2009) found through numerical modelling using TAPM that there was very little chance that PM10 concentrations in Clyde were contributing to Alexandra's PM10 concentrations. This phenomenon has been experienced before, with drainage winds transporting polluted air from Rangiora to Kaiapoi; two towns to the north of Christchurch (Hamilton et al., 2004). In Hamilton et al.'s study however, drainage winds were stronger, having originated in the foothills of the Southern Alps, and therefore had more potential to transport polluted air from one town to the other, whereas the winds in the Alexandra basin during high pollution events are generally too light to achieve this.

It is also unlikely that cold air avalanching is occurring in Alexandra. This research has shown that, under calm conditions, drainage winds from the hills to the south of Alexandra develop at night time, whereas these winds would need to be in the opposite direction in order to facilitate cold air avalanching. This is in line with the findings of West (2008), where measured wind direction under anticyclonic conditions was from the south and south-east, indicating the presence of drainage winds off the hills and towards the town, rather than cold air avalanching down the Clutha Gorge.

Through surveying household burning behaviour, West (2008) found that burners were refuelled at two hour intervals during the evening (although this was based on a small number of surveys), and assumed that the most efficient combustion, and therefore the lowest emissions, would occur at the end of each two hour period. West (2008) found that fuel was added to burners at 1700, 1900, and 2100 hours, which would mean that emissions would be greatest at these times, and then decrease until the next refuel. This trend is not visible in Figure 4.6, and it is unlikely that fuel is loaded at the same time between households.

Another possibility is that the bimodal evening peak in Alexandra is site specific and therefore not representative of the whole town. In which case, the bimodal peak may be due to burning behaviour in the immediate vicinity of the monitoring site, as suggested by West (2008), or due to drainage flows moving clean air over the monitor, as suggested by Conway (2009). It seems likely that the bimodal peak is site specific; however, further research is needed to determine the exact cause.

In Mosgiel, it seems likely that the smaller evening peak in PM10 concentrations is due to clean air being moved over the monitoring site, and polluted air being transported away from it. For high pollution days in Mosgiel (Figure 4.6b), the evening peak in air pollution is smaller than the morning peak and the highest night time concentration occurs at 0100 hours. This is an unusual pattern, and is more likely to be a reflection on the location of the monitoring site, rather than a reflection of overall emission patterns in Mosgiel.

6.5 Alternative Measures for Reducing PM10 Air Pollution

Ultimately, the best way to reduce PM10 air pollution is to prevent emissions from being released into the atmosphere in the first place. In this section, several methods for achieving this are offered. Quality of housing is an important factor in reducing the amount of fuel that is burnt, and therefore, the amount of emissions that are released. If the extent and efficiency of insulation in a house is up to standard then it will retain heat for longer, meaning less fuel will be needed. In Airshed 1 towns, the Otago Regional Council offers a subsidy on installing adequate under floor and ceiling insulation and on upgrading to a compliant wood burner or non emitting heating source such as a heat pump (Otago Regional Council, 2010).

The type of wood burnt is also an important factor. This includes the species, moisture content, and size and shape of logs burnt, as well as the manner in which the wood is stored. Users of wood burners can also reduce emissions through their skills and knowledge of how to use the appliance most efficiently. But again, this comes down to the attitude of the individual, and is not easily enforced. Similarly, if the users of burners can recognise the atmospheric conditions that will result in high air pollution levels, non-emitting heat sources can be used on those days.

The lack of knowledge demonstrated by the user of an appliance may be bypassed through the development of a micro-computer developed by a Canterbury entrepreneur. The computer assesses the combustion conditions within the firebox and adjusts the air intake accordingly so that combustion is optimised (Fisher et al., 2007). For example, when a new piece of wood is loaded into the firebox the air intake would be increased to initiate combustion. This system works with primary and secondary combustion within the firebox, therefore it is assumed that the air intake is reduced once combustion has occurred so that the fuel is not consumed too quickly, thus increasing cost. It is understood that greatest emissions from wood burning appliances occur when the appliance is on a low setting, which causes combustion to be incomplete. This setting is often chosen late at night so that the fire will continue to heat the house through the night, or so that wood is burnt conservatively. However, if the appliance functions with primary and secondary combustion, emissions should be minimised.

Another similar technology called SmartBurn has been devised in Australia. In this case, a tube containing certain non-toxic ingredients is placed within the firebox. When heated, vapours are released from the tube which improve the efficiency of fuel combustion and reduce emissions. The greatest reduction of emissions (50% reduction) occurs when the appliance is on a low setting, with a mean reduction of 37%. The SmartBurn costs $AUD46 and needs to be replaced after 900 hours (Fisher et al. 2007), which means that the user must be motivated enough to reduce emissions that they are willing to spend money to do so. The micro-computer would also require initial spending, but once acquired the power it consumed would be minimal.

Another technology – a scrubbing device – has also been developed by a Canterbury entrepreneur, which reduces emissions through scavenging once they are in the flue of the appliance. The emissions in the flue are hit with fine droplets of water, causing them to fall out of suspension, thus preventing them from being released into the atmosphere. The particles are then removed from the water, which is recycled. During this process, the water is heated and can also be used to heat the house in radiators or under-floor heating. The only potential issue is in the disposal of the particulates, which may contain contaminants (Fisher et al., 2007).

6.6 Summary

In this study, the agreement between modelled and observed meteorological conditions was fairly good, and it is expected that the error could be further reduced through fine tuning TAPM's parameters so that they match those of the study area more closely. In particular, soil moisture, deep soil temperature, and sea surface temperature all affect and influence the modelled air temperatures. The default settings may not necessarily be appropriate for the New Zealand environment, especially during wintertime and under topographically induced climates. If the modelled meteorological conditions are not well simulated then this adversely affects modelled PM10 concentrations. Therefore, it is imperative that the model set-up reflects the physical environment of the study area as closely as possible, and to achieve this the observational data needs to be reliable. This includes emissions data, which were somewhat restrictive, due to a lack of spatial variability. This said, this study has shown that TAPM is able to simulate meteorological and air pollution processes, and is a valuable tool for air quality management, adding a second and third dimension to the current point source data.

Based on this research, it appears that neither of the ORC monitoring sites are located in the area of worst air quality, which is a requirement of the NES. This is particularly worrying for Mosgiel, as the main (evening) peak in emissions does not seem to be well captured at the current monitoring site when drainage winds are in operation. This means that the air pollution problem in Mosgiel may be worse than what is presently measured. Regardless of whether this is the case or not, it is highly unlikely that either town will reach the NES for air quality by 2013, even with restrictive standards on burner emissions. This will prohibit the granting of resource consents that allow emissions to the air, but the air quality problem will still remain, as will the adverse effect of air pollution on human health. However, recent technologies provide an optimistic outlook, although it remains largely up to the desire of the user, or lack thereof, to implement these.

7

Conclusion

7.1 Introduction

The key aims of this research were to:

- Investigate the air pollution meteorology of Alexandra and Mosgiel through point source observational data.
- Use numerical modelling to gain insight into spatial and temporal trends in PM10 concentrations and meteorological processes contributing to poor air quality.
- Determine whether the current ORC monitoring sites are in the area of worst air quality for each town.
- Calculate the necessary percentage reduction in emissions required for each town so that the NES can be achieved.

In this chapter, the key findings of this research will be presented in regard to how these findings contribute to the growing understanding of the air pollution meteorology of each town. Directions for future research will also be presented, and the chapter will close with concluding thoughts on domestic air pollution.

7.2 Summary of Key Findings

Observational data has shown that there is an inverse relationship between PM10 and temperature, and PM10 and wind speed, although this relationship is more pronounced in Alexandra than in Mosgiel. The number of breaches that have occurred per year in each town since monitoring began shows that significant inter-annual variation is occurring. However, this is likely to be due to atmospheric controls on emissions rather than variation in the emissions between years. Based on the large number of breaches experienced in 2008, the winter of this year was selected for modelling. In Alexandra, TAPM correctly forecast 78% of the breach days, and correctly forecast 66% of the time overall. In Mosgiel, TAPM correctly forecast only one of the nine breaches experienced in 2008, but correctly forecast 71% of the time overall, due to a large number of non-breaches being correctly predicted. As well as providing meteorological and PM10 data to compare against the observational data, TAPM also provided meteorological data through the vertical profile, characterised the spatial wind regime around each town, and calculated spatial PM10 concentrations in each town, thus shedding light on these processes, which is something that could not have been achieved through analysing point source data alone.

A limiting factor imposed on the model was a lack of spatial variability in the emissions data. However, for Alexandra at least, a homogenous source area of emissions proved to be satisfactory, with modelled concentrations matching observed concentrations closely over a 10 day period. This may be because housing density is more constant in this town, or it may be due to the fact that Alexandra is situated in the bottom of an inland basin, thus, drainage winds will facilitate the build-up of air pollution in the bottom of the basin, as observed. In Mosgiel however, the assumption of homogenous emissions across the source area was not satisfactory. This is due to the fact that the eastern half of Mosgiel is dominated by parks, green spaces and retirement homes, whereas the western half of Mosgiel is dominated by higher density housing. Adding to this is the fact that, unlike in a basin where pollution is trapped at the lowest elevation, Mosgiel is bounded by hills on only three sides, and is open to the south-west. Because of this, under calm conditions, drainage winds transport polluted air from east to west, thus adding to the already higher levels of pollution in the west.

This research has also indicated that the monitoring sites in each town may not be situated in the area of worst air quality, which means that actual levels may be worse than those currently measured. Because of this, it is believed that the diurnal trends in PM10 concentrations, such as the bimodal evening peak in Alexandra, and the unusually low evening peak in Mosgiel, are site specific phenomena, and therefore not representative of the whole town. If PM10 concentrations are to be measured as accurately as possible, then both monitoring sites should be relocated to the area of worst air quality in each town.

The final aim of this research was determine the necessary percentage reduction in emissions required in order for the NES to be achieved in each town. Because TAPM overestimated PM10 concentrations by 41% in Alexandra and 48% in Mosgiel over the four month modelling period, accurate percentage reductions could not be calculated. It is not known if the overestimation of modelled PM10 concentrations was caused by inaccuracy in the emissions inventory, inaccuracy in the modelling, or a combination of the two.

7.3 Recommendations for Future Research

If future research is to be conducted using TAPM to model the air pollution meteorology of small towns, it would be advisable to source input data that is as accurate as possible, as the model can only perform to the level of quality of the information that is given to it. This would include a terrain file with a greater spatial resolution so that features such as the height of hills are accurately represented. When modelling PM10 concentrations it would also be ideal to obtain or create an emissions inventory that is up to date and represents the spatial variability of emissions based on features such as land use, housing density, and burner type.

An interesting study would be to determine the effect that upgrading to fully compliant burners would have on PM10 concentrations. To achieve this, the number of burners in the town would need to be known, as well as the average number of kilograms of fuel used per day. The emissions could then be set at 0.7 g kg^{-1}, or 1.5 g kg^{-1}, depending on whether the town is an Airshed 1 or Airshed 2 town. TAPM could then be run under stable atmospheric conditions, which would give a worst case scenario of pollution concentrations using a best case scenario of emission rates.

This research has suggested that the bimodal evening peak in PM10 concentrations in Alexandra during high pollution events is site specific, and therefore does not occur over the whole town. However, further research is required in order to determine whether this is true or not. To do this, PM10 would need to be measured at other parts of the town between 1800 and 2200 hours under calm conditions to see whether PM10 concentrations decrease and then increase again during this time. Similarly, further measurements of PM10 concentrations in Mosgiel would help clarify to processes of pollution transport thought to be occurring there.

7.4 Concluding Thoughts

When looking at the bigger picture of the air pollution problem in these two towns, it does not seem that emissions levels are being reduced enough, if at all, and it appears highly unlikely that the targets of the NES will be achieved, especially if the timing for this remains at 2013. It will be interesting to see what effect the upgrade to compliant burners will have on pollution levels, although this is unlikely to solve the air pollution problem entirely, especially in Alexandra. Additional to the upgrade to compliant burners, alternative measures for reducing PM10 emissions, such as those outlined in Section 6.5, should be looked into, and possibly enforced, if domestic burning appliances are to remain in Alexandra and Mosgiel.

References

Barnett, A., Williams, G., Schwartz, J., Best, T., Neller, H., Petroeschevsky, A. and Simpson, R. (2006) 'The effects of air pollution on hospitalizations for cardiovascular disease in elderly poeple in Australian and New Zealand cities', *Environmental Health Perspectives* 114(7): 1018-1023.

Barnett, A., Williams, G., Schwartz, J., Neller, H., Best, T., Petroeschevsky, A. and Simpson, R. (2005) 'Air pollution and child respiratory health: a case-crossover study in Australia and New Zealand', *American Journal of Respiratory and Critical Care Medicine* 171(11): 1272-1278.

Beta attenuation monitor (BAM) 1020 Particulate Monitor Operation Manual (2001), unpublished manual.

Blewett, S.E. (1998) *What's in the Air: Natural and Man-made Air Pollution*, California: Seaview Publishing.

Boubel, R. (1994) *Fundamentals of Air Pollution*, San Diego: Academic Press.

Broadbent, A. (2010) 'Measurements and modelling of wintertime PM10 air pollution – Milton, Otago', Department of Geography, University of Otago: unpublished MSc thesis.

Broadbent, A., Cullen, N. J. and Zawar-Reza, P. (2010) 'Wintertime numerical modelling of PM10 air pollution in Milton, Otago, New Zealand: boundary layer structure, effects of data assimilation, and reaching national environmental standards', *Air Quality and Climate Change,* in press.

Colls, J. (2002) *Air Pollution* (2nd ed.), London: Spon Press.

Conway, J. (2006) 'Clean southern air? Spatial variations of particulate matter pollution in Invercargill', Department of Geography, University of Otago: unpublished BSc (hons) dissertation.

Conway, J. (2009) 'Investigation into the interaction of PM10 emissions from Clyde and Alexandra', Otago Regional Council: unpublished environmental science committee report.

Conway, J., Spronken-Smith, R. and Zawar-Reza, P. (2007) 'The clean air down there? Spatial patterns of particulate matter pollution in Invercargill, New Zealand', *Clean Air and Environmental Quality* 41 (3): 19-25.

Fisher, G., Kjellstrom, T., Kingham, S., Hales, S. and Shrestha R. (2007) 'Health and air pollution in New Zealand', Ministry for the Environment, Ministry of Transport: unpublished report.

Fisher, G., Kuschel, G. and Mahon, K. (2005) 'Straight and curved line paths (SLiPs & CLiPs): Developing the targets and predicting the compliance', NIWA: unpublished report.

Geller, M., Fine, P. and Sioutas, C. (2004) 'The relationship between real-time and time-integrated coarse (2.5-10 micron), intermodal (1-2.5 micron), and fine (<2.5 micron) particulate matter in the Los Angeles Basin', *Journal of the Air and Waste Management Association* 54(9): 1029-1039.

Gimson, N., Olivares, G., Khan, B. and Zawar-Reza, P. (2007) 'Dispersion modelling in New Zealand – Part 1 – Assessment of meteorological models', Christchurch: unpublished report prepared by Golder Associates.

Hales, S., Salmond, C., Town, G., Kjellstrom, T. and Woodward, A. (2000) 'Daily mortality in relation to weather and air pollution in Christchurch, New Zealand', *Australian and New Zealand Journal of Public Health* 24 (1): 89-91.

Hamilton, B., Spronken-Smith, R. and Zawar-Reza, P. (2004) 'Spatial patterns of particulate episodes in Rangiora and Kaiapoi, Canterbury, New Zealand', *Clean Air and Environmental Quality* 38 (1): 26-32.

Hien, P., Bac, V., Tham, H., Nhan, D. and Vinh, L. (2002) 'Influence of meteorological conditions on PM2.5 and PM2.5-10 concentrations during the monsoon season in Hanoi, Vietnam', *Atmospheric Environment* 36: 3473-3484.

Hirdman, D. (2006) 'Sensitivity analysis of the mesoscale air pollution model TAPM', University of Canterbury: unpublished MSc thesis.

Hurley, P. (2008a) 'The air pollution model (TAPM) version 4, Part 1: Technical description', unpublished CSIRO marine and atmospheric research paper, no. 25.

Hurley, P. (2008b) 'The air pollution model (TAPM) version 4, user manual', unpublished CSIRO marine and atmospheric research internal report, no. 5.

Hurley, P., Edwards, M. and Luhar, A. (2008) 'The air pollution model (TAPM) version 4, Part 2: Summary of some verification studies', unpublished CSIRO marine and atmospheric research paper, no. 26.

Hurley, P., Manins, P., Lee, S., Boyle, R., Ng, Y. and Dewundege, P. (2003) 'Year-long, high-resolution, urban airshed modelling: Verification of TAPM predictions of smog and particles in Melbourne, Australia' *Atmospheric Environment* 37: 1899-1910.

Jacobson, M.Z. (2002) *Atmospheric Pollution: History, Science, and Regulation*, Cambridge: Cambridge University Press.

Koenig, J.Q. (2000) *Health Effects of Ambient Air Pollution: How Safe is the Air We Breathe?* Boston: Kluwer Academic Publishers.

Luhar, A. and Hurley, P. (2003) 'Evaluation of TAPM, a prognostic meteorological and air pollution model, using urban and rural point source data', *Atmospheric Environment* 37: 2795-2810.

Luhar, A., Galbally, I. and Keywood, M. (2006) ‘Modelling PM10 concentrations and carrying capacity associated with woodheater emissions in Launceston, Tasmania’, *Atmospheric Environment* 40: 5543-5557.

Manuell, D. (ed.) (2000) ‘Air pollution measurement manual: A practical guide to sampling and analysis’, unpublished manual: Clean Air Society of Australia and New Zealand.

Ministry for the Environment (2010) online: *Proposed Amendments to the National Environmental Standard for Air Quality*, http://www.mfe.govt.nz/news/nesaq-workshop-presentation.pdf (accessed December 2010).

Ministry for the Environment New Zealand (2010) online: *National Environmental Standards: Airsheds*, http://www.mfe.govt.nz/laws/standards/airsheds/index.html (accessed May 2010).

Monn, C., Braendli, O., Schaeppi, G., Schindler, C., Ackermann-Liebrech, U., Leuenberger, P. and SAPALDIA TEAM (1995) ‘Particulate matter <10 micron (PM10) and total suspended particulates (TSP) in urban, rural and alpine air in Switzerland’, *Atmospheric Environment* 29 (19): 2565-2573.

Mulliner, T., Hager, T., and Spronken-Smith, R. (2007) ‘Temporal patterns of PM10 in a small southern town in New Zealand’, *Clean Air and Environmental Quality* 41 (2): 27-33.

National Institute of Water and Atmospheric Research (NIWA) (2001) ‘The climate of Otago: Patterns of variation and change’, Dunedin: unpublished report for the Otago Regional council.

National Institute of Water and Atmospheric Research (NIWA) (2010a) online: ‘The climate of New Zealand: Inland South Island’, http://www.niwa.co.nz/education-and-training/schools/resources/climate/overview/map_i_south (accessed June 2010).

National Institute of Water and Atmospheric Research (NIWA) (2010b) online: ‘The climate of New Zealand: Southern New Zealand’, http://www.niwa.co.nz/education-and-training/schools/resources/climate/overview/map_south (accessed June 2010).

Oke, T.R. (1987) *Boundary Layer Climates* (2nd ed.), London: Routledge.

Osman, J (2007) ‘Temporal variations in South Dunedin PM10’ Department of Geography, University of Otago: unpublished BSc (hons) dissertation.

Otago Regional Council (2005) ‘Ambient air quality in Otago: Particulate Matter 1997-2004’, Dunedin: unpublished Otago Regional Council report.

Otago Regional Council (2006) ‘Central Otago home heating and air pollution: 2006 survey findings’, Dunedin: unpublished Otago Regional Council report.

Otago Regional Council (2009a) 'Ambient air quality in Otago: Particulates 2005-2008', Dunedin: unpublished Otago Regional Council report.

Otago Regional Council (2009b) 'Mosgiel spatial PM10 study', Dunedin: unpublished Otago Regional Council report.

Otago Regional Council (2010) 'Clean heat clean air: Clean heat assistance programme', http://www.orc.govt.nz/Documents/Content/Information%20Services/Air/CleanHeatCleanAir-July2010-web.pdf (accessed November 2010).

Reese, T. (2009) 'TAPM: A valuable tool for the assessment of atmospheric processes during a high pollution event in Mosgiel?', Department of Geography, University of Otago: unpublished BAppSci dissertation.

Sturman, A. (2001) 'Synoptic controls on the weather', in A. Sturman and R. Spronken-Smith (eds) *The Physical Environment: A New Zealand Perspective*, Melbourne: Oxford University Press.

Sturman, A.P. and Tapper, N.J. (2006) *The Weather and Climate of Australia and New Zealand* (2nd ed.) Melbourne: Oxford University Press.

Tate, A. and Spronken-Smith, R. (2008) 'A preliminary investigation of the air pollution meteorology of Alexandra, Central Otago, New Zealand', *Clean Air and Environmental Quality* 42 (2): 15-21.

West, O. (2008) 'Wintertime PM10 in an inland basin: Alexandra, Central Otago, New Zealand', Department of Geography, University of Otago: unpublished MSc thesis.

Whiteman, D. (2000) *Mountain Meteorology: Fundamentals and applications*, New York: Oxford University Press.

Wilton, E. (2006) 'Air Emission inventory – Dunedin, Mosgiel and Alexandra 2005', Christchurch: Environet Ltd, unpublished report prepared for the Otago Regional Council.

Zawar-Reza, P. and Sturman, A. (2008) 'Application of airshed modelling to the implementation of the New Zealand National Environmental Standards for air quality', *Atmospheric Environment* 42: 8785-8794.

Zawar-Reza, P. and Spronken-Smith, R. (2005) 'Air pollution climatology', in J. Oliver (ed.) *Encyclopaedia of world climatology,* Cornwall: Springer: 21-32.

Zawar-Reza, P., Kingham, S. and Pearce, J. (2005b) 'Evaluation of a year-long dispersion modelling of PM10 using the mesoscale model TAPM for Christchurch, New Zealand', *Science of the Total Environment* 349: 249-259.

Zawar-Reza, P., Sturman, A. and Hurley, P. (2005a) ‘Prognostic urban-scale air pollution modelling in Australia and New Zealand – A review’, *Clean Air and Environmental Quality* 39 (2): 41-45.

Zawar-Reza, P., Sturman, A. and Spronken-Smith, R. (2003) ‘Validation of The Air Pollution Model (TAPM) for prediction of pollution levels during winter of 2000, over Christchurch, New Zealand’, Lodź, Poland: *5th International Conference on Urban Climate,* 1-5 Sept 2003. 2: 201-204.

Zawar-Reza, P., Titov, M. and Sturman, A. (2005c) ‘Dispersion modelling of PM10 for Christchurch, New Zealand: An intercomparison between MM5 and TAPM’, Proceeding of the 17th International Clean Air and Environment Conference, Hobart, Australia, 3-6 May 2005.

Personal Communications

McVie, C. (2010) Environmental Officer: Industrial Management, Otago Regional Council, email 27 April 2010.

Mills, D. (2010) Environmental Officer, Otago Regional Council, email 23 November 2010.

Appendix A

In addition to the Otago Regional Council (ORC) data and West's (2008) data, hourly wind speed and direction data were also obtained from the NIWA online database for the 2007 – 2009 period. NIWA's wind instruments are at a height of 10 m above ground level, whereas the ORC data and West data are at heights of 3 m and 2.5 m respectively. If wind speeds are under-estimated due to the heights of the ORC and West instruments, it would be expected that the NIWA data would exhibit greater wind speeds and may also show a dominant wind direction if there was one. However, and especially during winter (Figure A.1b), wind speeds are low and come from all directions, which indicates that the wind regime in Alexandra is driven by surface heating and cooling rather than by the synoptic situation. The greater percentage of wind speeds less than 0.5 m s^{-1} coming from the north-north-east are likely to be drainage winds from the Clutha Gorge (see Figure 3.5).

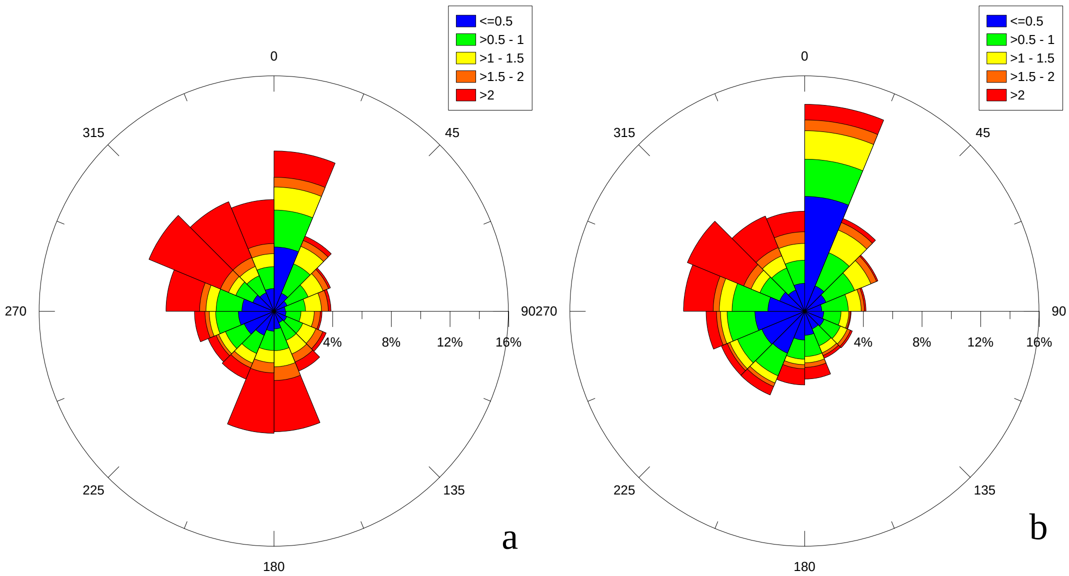

Figure A.1 Wind roses for Alexandra using all wind data (a) and winter wind data only (b) from NIWA data.

Appendix B

From 1400 hours on 24 June 2008 until 0800 hours on 25 June 2008 (a total of 19 hours) there were no temperature data recorded at the Otago Regional Council (ORC) monitoring site (for reasons unknown). This data gap occurred within Case Study One (Section 5.5), which ran from 21 – 30 June 2008.

A linear regression was carried out on the ORC temperature data and West's (2008) data, which were recorded at an automatic weather station 2 km to the north-west of Alexandra (Figure 3.5), with the 19 hours that were missing from the ORC data removed from the West data as well. The resulting linear regression equation (Figure B.1) was then used to calculate the temperature for the hours that were missing.

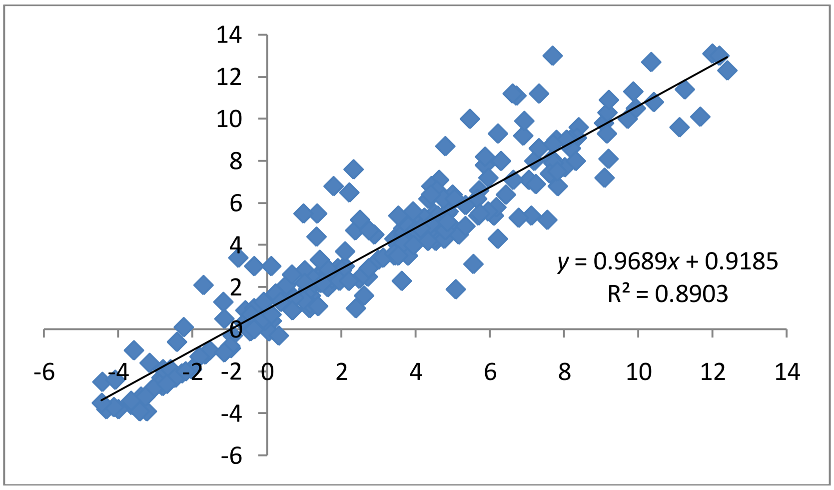

Figure B.1 Linear regression of West (2008) temperature data and ORC temperature data, and regression equation, where *y* is the ORC data and *x* is the West data.