Report Prepared for Otago Regional Council

Investigating Meteorological Interventions for Improving Air Quality in Airshed 1 Towns

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Table of Contents

Executive Summary

Some Central Otago towns experience poor air quality in the winter months, primarily due to meteorological conditions that limit the dispersal of smoke from wood burners used for domestic heating. The potential for modifying the meteorological state of the atmosphere to reduce the concentration of particulate matter pollution of 10 microns in size or smaller (PM10) has been assessed here. No examples of such meteorological intervention schemes for improving air quality were found in the literature. The effect of several hypothetical schemes to modify the structure or circulation of the atmosphere in various ways, and their effects on PM10 concentrations during high-pollution nights, were assessed using an air pollution dispersion model. These schemes included using frost fighting fans, emulating a naturally occurring 'low-level jet' wind, and drawing air down the Clutha River gorge. Each of these schemes would require significant energy inputs (on the order of 10 MW or more) and would need to be run continuously during periods of strong inversions and resultant periods of limited dispersion - conditions typical of Alexandra winter nights. With continuous operation, moderate reductions in PM10 concentrations were found for all schemes. To reduce PM10 concentrations to levels needed to meet the National Environmental Standard for Air Quality (NESAQ), it is likely that two or more schemes would need to be run simultaneously.

No scheme is likely to succeed in reducing PM10 concentrations to consistently meet required NESAQ levels within reasonable energy input limits.

Introduction

The poor air quality that some Central Otago towns experience in the winter months is primarily caused by meteorological conditions that limit the dispersal of smoke from domestic solid fuel heating. At present, the Otago Regional Council (ORC) accepts that wood-burners are currently necessary to provide residents with adequate heating during winter months. However, even with a significant portion of wood-burners being upgraded to MfE-compliant models during the past 10 years, non-dispersing smoke still creates particulate matter (PM10 - denoting particular matter of 10 micrometres in diameter or smaller) levels that regularly exceed the standard set in the National Environmental Standard for Air Quality (NESAQ). The ORC is looking to explore novel methods to reduce PM10 concentrations. In particular, the ORC has asked for an assessment of the potential of interventions that modify atmospheric boundary layer meteorology to reduce PM10 concentrations through enhanced dispersion of the pollution. This report summarizes an assessment of the ways in which the boundary layer could be modified, and the effects of such modifications on PM10 concentrations.

For the purposes of this report, options for boundary layer interventions are investigated specifically for Alexandra which has been chosen due to the more highly developed understanding of air pollution meteorology above Alexandra compared to other Central Otago towns. In addition, the PM10 levels experienced in Alexandra are, on average, the highest within the region. The results, however, will be broadly applicable to most Central Otago towns. To date there has been significant interest in winter air quality in Alexandra shown by students, researchers, local and central government as well as the public. ORC has monitored and reported on hourly PM10 concentrations, along with air temperature, wind speed and wind direction in Alexandra since mid-2005. Our understanding of how meteorology contributes to high pollution days in Alexandra has benefited from a large number of published studies (Tate and Spronken-Smith, 2008; Trompetter et al., 2010; Tate et al., 2011; Cullen et al., 2012; Trompetter et al., 2013; Ancelet et al., 2014) and University theses (West, 2008; Tate, 2010; Ancelet, 2012; Price, 2014;). Because Alexandra's meteorological setting is similar to other Central Otago towns, which regularly exceed NESAQ, the conclusions reached here are likely to be applicable elsewhere.

This report is structured in four sections:

1. A description of the meteorological setting of Central Otago towns including information on atmospheric inversion characteristics.
2. A brief overview of what characteristics of the inversion could be changed – including examples of interventions employed in vineyards and orchards.
3. An assessment of the effect of boundary layer intervention schemes on PM10 concentrations using dispersion modelling.
4. An assessment of the feasibility and scaling of boundary layer intervention schemes to the town scale.

Detailed information on the methods used to generate specific results are contained in appendices.

1 Meteorological setting

Particulate matter concentrations exceeding the NESAQ standard are frequently tied to the atmospheric conditions. High PM10 levels are typically associated with clear, cold weather with weak synoptic pressure gradients. Under these conditions, cooling of the surface through the emission of infra-red radiation (so-called radiative cooling) after sunset creates a temperature inversion (increasing temperature with height) that suppresses the turbulent motions close to the surface that would otherwise disperse PM10 to higher altitudes. In basins such as Alexandra these radiative inversions are further enhanced by drainage flows that transport cold air from areas of higher elevation into the town. In Alexandra, these winds are light (<1 ms^{-1}) and generally flow from the Northeast and Southeast directions over the town area (Tate, 2011; Price, 2014). These low wind speed inversion conditions limit the turbulence within the near-surface atmosphere (or surface boundary layer; SBL) and it becomes decoupled from the overlying atmosphere (or residual layer; RL). Decoupling means that there is little, if any, exchange of air between the SBL and the RL which limits the dispersal of PM10 emissions. In large valley systems found in Central Otago, the SBL and RL can be further decoupled from the large scale (synoptic) weather systems creating isolated layers of air with limited volumes in which any surface emissions are trapped. Analyses by West (2008) and Price (2014) indicate that high PM10 conditions occur not only during anticyclonic conditions but during a range of different weather conditions and that the decoupling from synoptic scale weather patterns occurs frequently.

In Alexandra, which is located on the floor of a broad basin (Fig. 1.1), drainage of cold air from the surrounding hills converges over the town creating a pool of cold air which strengthens the inversion. Although Alexandra is located at the entrance to the Roxburgh Gorge down which the Clutha River flows, little drainage of air down the gorge occurs since the gorge is long and constricted. Furthermore, the river surface during the winter months is likely to be warmer than overlying air and this weakens the downriver (katabatic) driving force of the drainage winds.

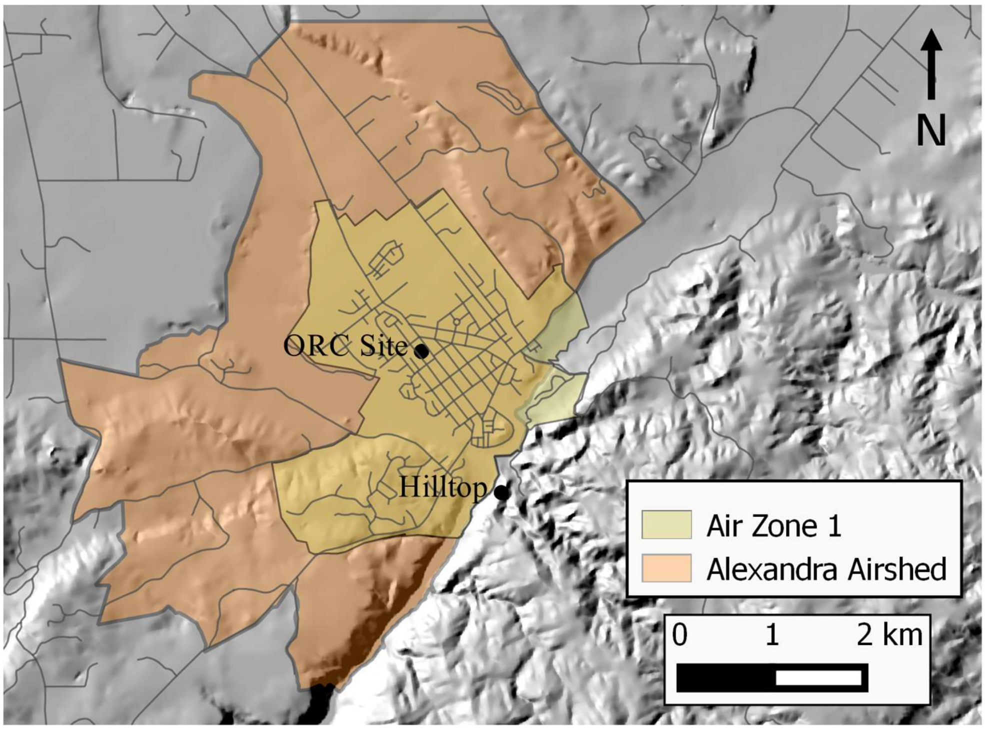


Fig. 1.1. A map of Alexandra, the relevant Air Zone and Airshed, and the key monitoring sites referred to in this report.

1.1. Temporal evolution of atmospheric stability

Consideration of the typical winter-time temporal evolution of atmospheric conditions in Alexandra provides a context for the typical daily cycle of PM10 concentrations. Figure 1.2 shows that during the night (i.e. between 6 pm and the following 9 am), wind speeds are, on average, light but not absolutely calm, usually between 0.5 and 1.0 m s^{-1}. During the day wind speed increases slightly.

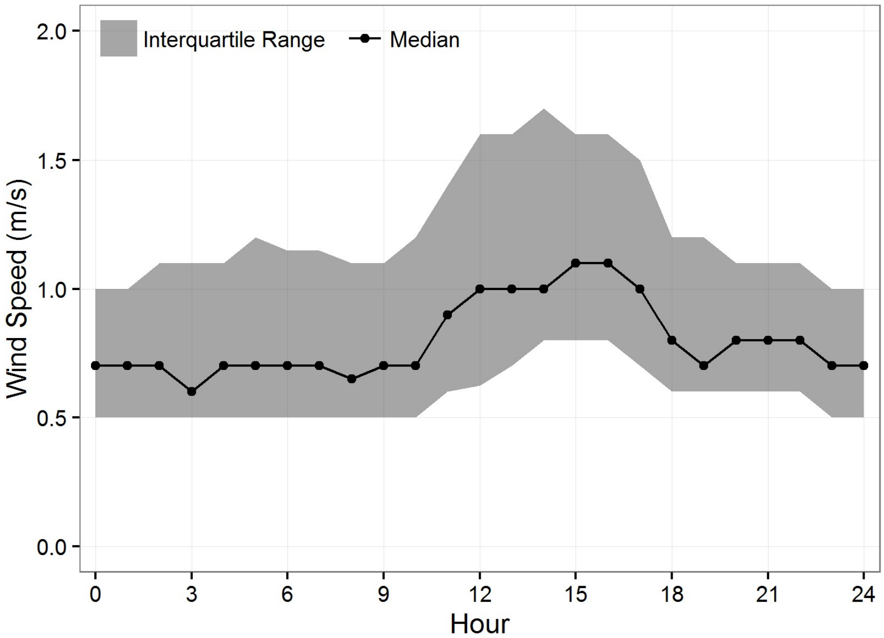


Fig. 1.2. The temporal evolution of wind speed from May to August 2009-2010 as measured at the NIWA Alexandra site (agent number: 36592). The shaded area shows the 50% of conditions that are closest to the median conditions (25% to 75% percentiles).

While at the time of the writing of this report no measurements of the strength and temporal variability of inversion conditions in Alexandra were available, results from a number of proxy studies are available. Price (2014) explored the time average atmospheric stability in Alexandra between 14 June and 20 August 2013. During the night the atmosphere is stable with a SBL height of 100 m or less. During the day (i.e. 10 am to 5 pm), the atmosphere becomes unstable with increased SBL heights of up to around 250 m. (Fig. 1.3). Days that exceed the NESAQ standard typically have markedly lower SBL heights and more stable conditions during the evening (larger positive values) and more unstable (larger negative values) during the day.

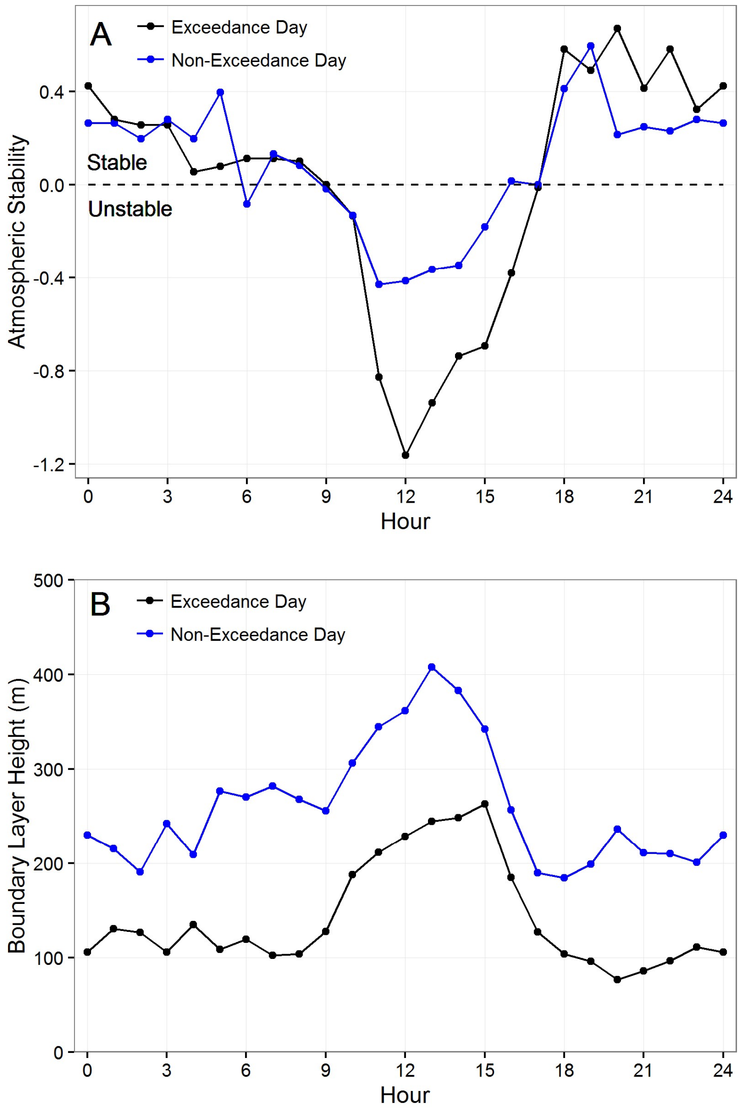


Fig. 1.3 The average daily cycle of atmospheric stability (A) and parameterised boundary layer height (B) during the winter of 2013 for exceedance days (38 days) and non-exceedance days (30 days). The metric for atmospheric stability used here is z/L, which is a dimensionless number describing the deviation from a neutral atmosphere. Figure modified from Price (2014).

In addition to the data collected by Price (2014), between 2008 and 2010 a thermometer was installed on a hilltop southeast of the Alexandra CBD (see Fig. 1.1) at an elevation 93 meters above the ORC monitoring site. While the air temperature recorded at the 'Hilltop' site is not entirely representative of the air temperature at the same altitude above the ORC monitoring site, the data can be used as a proxy for a measurement about 100m above the ORC site and thus used to calculate the strength of the inversion. At night, during the months of May to August, temperatures were typically around 1 °C cooler at the ORC monitoring site than at the hilltop site (Fig. 1.4). On average the inversion dissipates at around 10 am before re-forming around 6 pm.

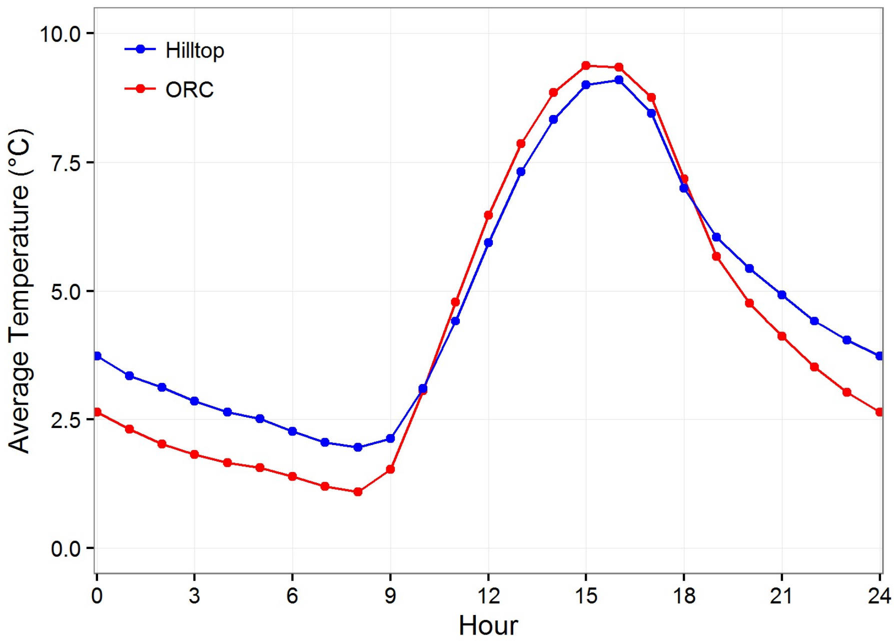


Fig. 1.4. Hourly average temperatures at the ORC monitoring station in town (ORC) and the Hilltop site southeast and 93 m above the CBD for the months of May to August 2009-2010.

To better characterize the frequency and magnitude of inversion conditions, an inversion index (I) was calculated as:

$$I = T_h - T_t - (LR\ x\ dz)$$

Where T_h is the temperature measured at the hilltop station, T_t is the temperature measured at the ORC monitoring site in town, LR is the standard environmental lapse rate of 0.0065 °C m^{-1}, and dz is the elevation difference between the two stations (93 m). Figure 1.5 shows a histogram of the hourly inversion indices over the period May – August for 2009 and 2010. In general, about half of the hourly periods had stable conditions (defined here as an inversion index >= 0.5) while a quarter of the hourly periods exhibited very strong stability (defined here as an inversion index >2). For daily conditions, 79% of the days sampled had stable conditions for at least 25% of the day, and 44% of the days sampled had strong stability for at least 25% of the day. During the same period (May – Aug, 2009 & 2010), 39% of the days sampled exceeded the NASEQ threshold for PM10 concentrations.

Additional analyses were made of the diurnal patterns of meteorology and PM10 concentrations for exceedance days and these are contained in Appendix D.

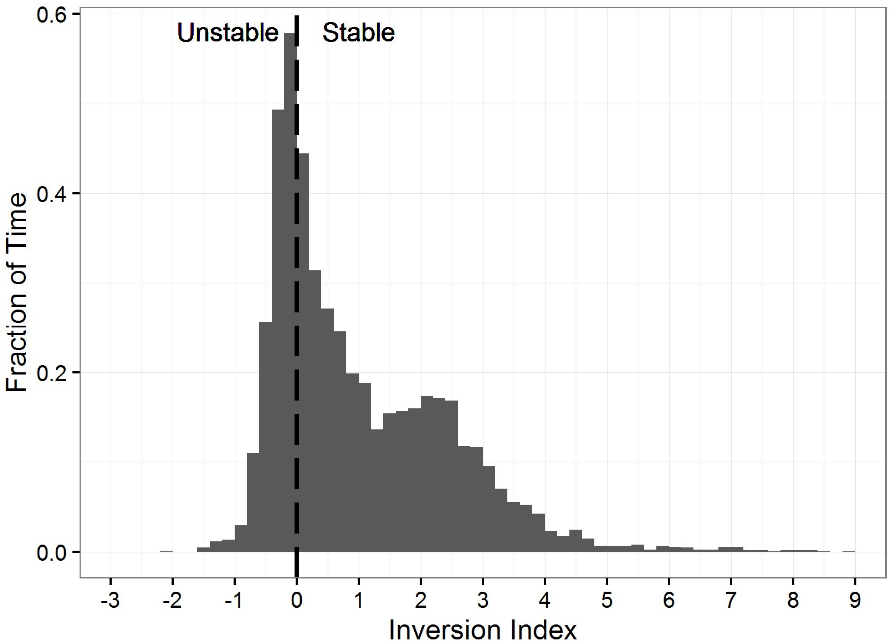


Fig. 1.5. Histogram of the inversion index for the months of May-August 2009-2010 showing a large proportion of stable conditions along with a peak at normal environmental conditions (0).

1.2. Temporal evolution of PM10 concentrations

The typical temporal evolution of PM10 concentrations in Alexandra (Fig. 1.6) is determined by both the atmospheric conditions and surface emissions of PM10. Owing to the formation of a temperature inversion around sunset, and an increase in PM10 emissions as people light their fires in the evening, PM10 concentrations rapidly increase. This is followed by a more gradual increase through the later evening to a peak sometime around midnight as emissions gradually build up within the SBL. After midnight, PM10 concentrations generally decrease but then peak again in the early morning in conjunction with the second peak in emissions. In Alexandra, a curious feature is observed where PM10 concentrations often decrease during the mid-evening; this mid-evening dip phenomenon is discussed in Section 1.3.

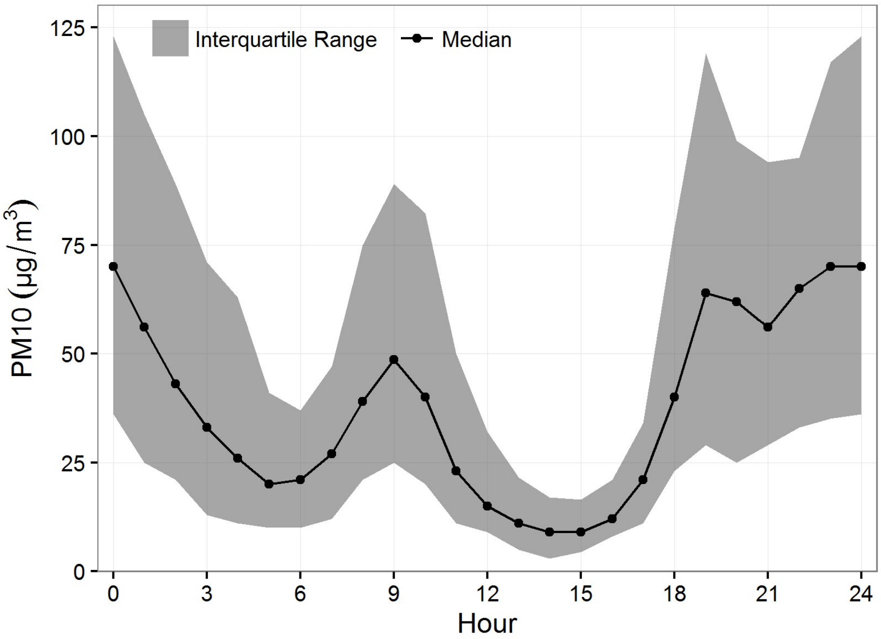


Fig. 1.6. Average temporal evolution of PM10 concentrations for all days between May and August 2009-2010 (inclusive). The shaded area shows the 50% of conditions that are closest to the median (25% to 75% percentiles).

In Alexandra, the morning peak does not appear to be associated with the mixing of high PM10 concentrations held aloft overnight in the RL given that PM10 concentrations at 26 m are similar to, or lower than, the surface PM10 concentrations (Ancelet et al., 2014; Fig. 1.7). Concentrations at 26 m also exhibit a morning increase indicating significant new emissions.

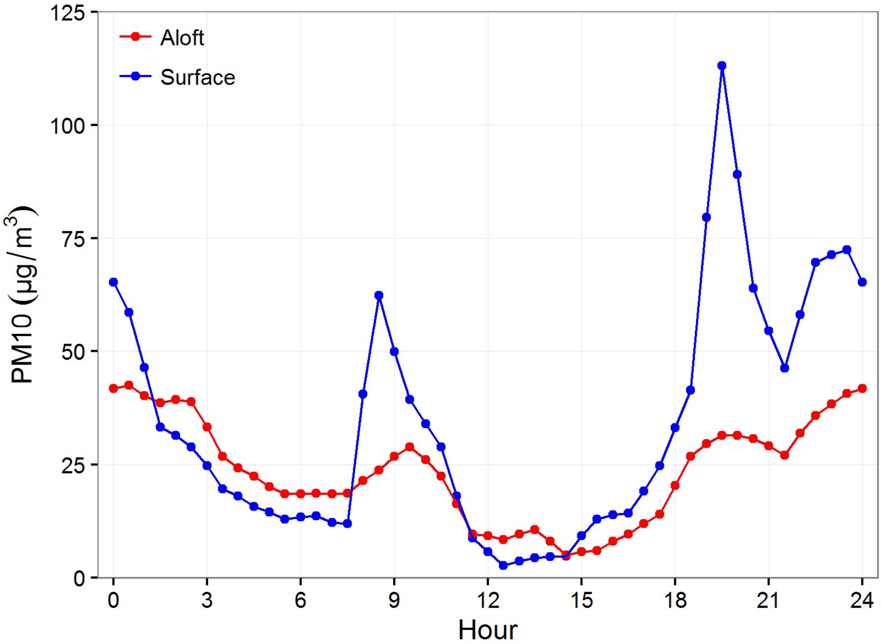


Fig.1.7. Temporal evolution of PM10 for selected periods between April to June, 2011, both at the surface and aloft at 26 m elevation. The diurnal cycle here differs significantly from Fig 1.6 as the data are only from 261 hours of coincident measurements. Figure modified from Ancelet et al. (2013).

During the day, solar heating creates unstable conditions at the surface and PM10 is effectively dispersed into the RL of the valley, resulting in low PM10 concentrations at the surface (Cullen et al, 2012; Price, 2014; Fig. 1.6). Some PM10 is likely retained within the valley SBL and adds to the following night's pollution, as evidenced by the increasing trend in PM10 during extended periods of settled weather (Price, 2014).

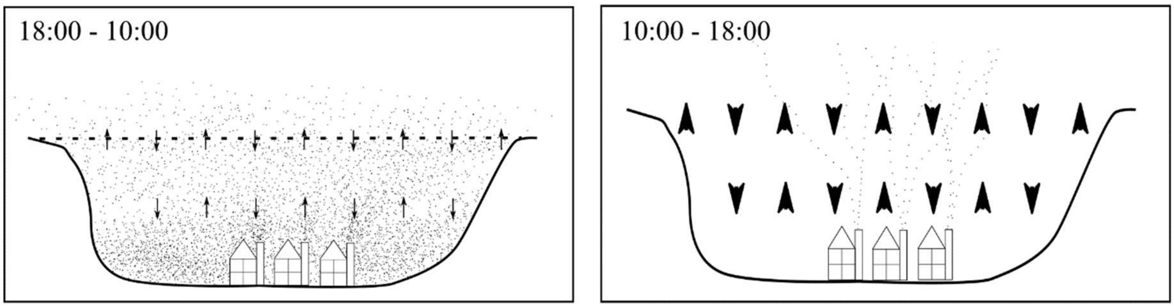


Fig. 1.8. A schematic of the typical inversion and PM10 characteristics in Alexandra. Night time radiative cooling decreases the mixing between the SBL and RL, which leads to high PM10 concentrations in the SBL. During the day, radiative warming at the surface increases the dispersion of PM10, reducing PM10 concentrations in the SBL.

1.3. Mid evening dip in PM10

PM10 concentrations in Alexandra often exhibit large decreases during mid-evening (8 to 10 pm), and this results in a distinct bimodal evening pattern of average PM10 concentrations (Figure 1.6). As discussed in ORC (2009), this pattern is not observed in other nearby towns (Fig 1.9), which indicates that it is a feature of the local meteorology, rather than a feature of the PM10 emissions profile for the town.

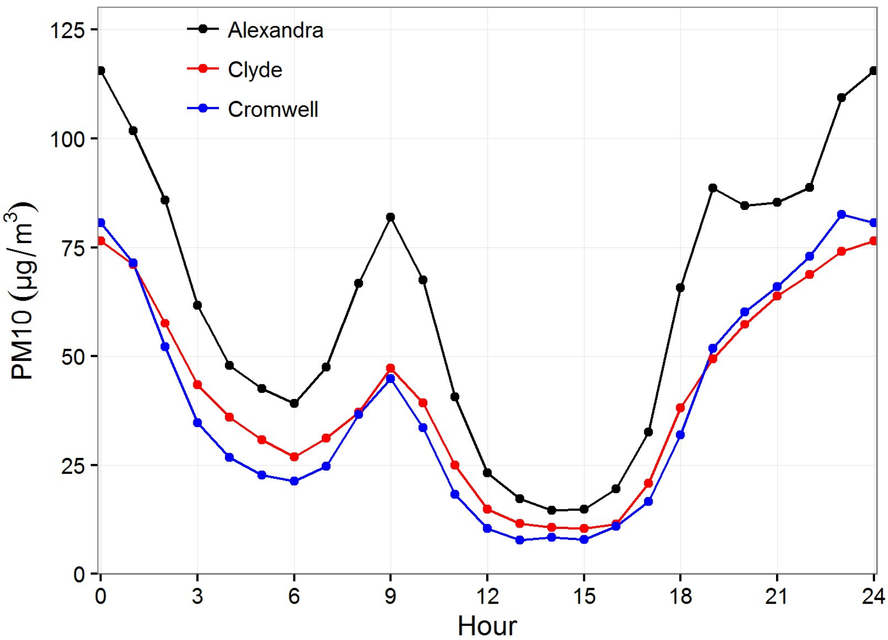


Fig. 1.9. The temporal evolution of PM10 concentrations in several Central Otago towns for May to September 2008 (ORC 2009)

While various explanations for this dip have been given, the most likely cause appears to be increased turbulence in the SBL that may be linked to a regional down valley breeze, or low level jet, that overlies the surface at a height of 60 to 120 m (Price, 2014). There is little evidence to support the idea that this dip results from horizontal transport of PM10 by cold air drainage winds at the surface. Rather, because the surface winds are variable in speed and direction, and show no correlation with the PM10 concentration dip, they are unlikely to be a driver of the mid-evening dip. Patterns of PM10 concentrations are highly variable in space and time through the mid-evening (West, 2008), so it could be that monitoring of wind speed and direction is insufficient to detect subtle changes in wind across Alexandra. If the pattern of reduced mid-evening concentrations is representative of the situation across Alexandra, it is likely that the daily mean and maximum PM10 concentrations are reduced from what would otherwise be experienced. This is supported by the fact that PM10 concentrations in other towns are, on average, 55% higher at midnight than at 7pm whereas in Alexandra PM10 concentrations are only 30% higher (Fig 1.9).

To achieve the NESAQ standard, only one exceedance of the 50 µg m^{-3} threshold is allowed annually. Therefore, the second highest daily concentration in each year must be 50 µg m^{-3} or less. Over the period 2005 to 2015, the average second highest daily PM10 concentration was 102 µg m^{-3}. Therefore, to meet the NESAQ standard, at least a 50% reduction in concentrations on high pollution nights is required. A more conservative approach that would meet the Otago goal of 35 µg m^{-3} would require a 65% reduction.

2 Possible interventions for reducing particulate concentrations

The potential to mitigate high PM10 concentrations through boundary layer interventions has not been significantly explored in the literature. Indeed, a detailed literature review did not return any examples of boundary layer intervention schemes that reduced air pollution levels through modifying near-surface atmospheric conditions. A list of key terms used in the literature search is given in Appendix A. As this is a relatively novel area of study, the most efficient approach is to identify the factors in the boundary layer conditions that can be modified and then identify any applicable processes from other fields (e.g. frost fighting, Section 2.2) and/or natural phenomena that could create these changes. In this section, we explore selected possible interventions and provide the requisite background for each potential intervention. We also consider other possible options for reducing PM10 concentrations that do not involve reductions in domestic solid fuel heating. The impacts of interventions are explored through dispersion modelling exercises described in Section 3, and the potential to implement these interventions on a town scale is evaluated in Section 4.

2.1. What can we change

The vertical dispersal (flux) of PM10 from the surface is dependent on both the vertical gradient of PM10 and the rate at which air is mixed (the diffusivity). If a strong vertical gradient of PM10 exists (i.e. clean air above), then the transport of PM10 up and away from the surface is enhanced over conditions where PM10 has a weak vertical gradient. Therefore, if clean air can be brought into layers of the atmosphere at tens of metres above the surface, and there is some mixing of air between the surface and those layers, PM10 concentrations at the surface will decrease. This vertical mixing is quantified by the diffusivity of the atmosphere which depends primarily on the vertical gradients of wind speed and temperature. Low diffusivity occurs under low wind speed conditions where turbulence (chaotic mixing of the atmosphere) next to the surface is very low. Diffusivity is reduced further by inversion conditions where the stable atmosphere (increasing air temperature with height) reduces vertical motions. In contrast, under unstable conditions, diffusivity increases as vertical movement of air parcels happens more easily. It follows that two possible options for promoting the dispersal of pollutants is to either increase wind speed and thereby decrease the strength of the inversion next to the surface to promote mixing, or introduce cleaner air some tens of metres above the surface

2.2. Frost fighting methods

Frost fighting techniques focus on raising the temperature near the surface to minimize the damage to frost-sensitive plants. These techniques can be divided into active and passive frost fighting techniques. Passive techniques are primarily careful site selection and tailoring the species planted to the site. Active techniques range from direct heating of vulnerable plants (e.g. heaters or sprinklers) to modifying inversion characteristics to bring warm air to the surface from aloft (i.e. wind machines and helicopters). Only the latter active techniques have relevance to mitigating PM10 concentrations and are described in further detail below.

2.2.1. Wind Machines

Wind machines work by increasing near surface turbulence to redistribute the heat that is already in the air by mixing the cold near-surface air with warmer air aloft. Wind machines typically have high installation costs (e.g. tens of thousands of dollars). The running cost for wind machines is related only to energy use and periodic maintenance.

Wind machines are typically designed either in horizontal or vertical flow configurations. Horizontal flow wind machines typically operate at a height of 10-11 m though this height is chosen to avoid wind machines hitting trees and there is no aerodynamic basis for this height selection (Snyder et al., 2005). Horizontal flow wind machines can increase the temperature at 1.5 m by about 30% of the temperature difference between 1.5 and 15 m (Ribero et. al., 2006; Snyder et al., 2005). Typically, when multiple machines are used, about 15 kW of engine shaft power is required per hectare (Snyder et al., 2005). The increase in average wind speed over a 4-hectare block was estimated at 0.15 m s^{-1} based on observations of peak wind speeds at 30, 70 and 100 metres from a 124 kW wind machine (Ribero et al., 2006). Fig. 2.1 shows the estimated distribution of wind speed around a frost fighting fan, showing the fast decay in wind speed due to surface friction and shear with the surrounding still air.

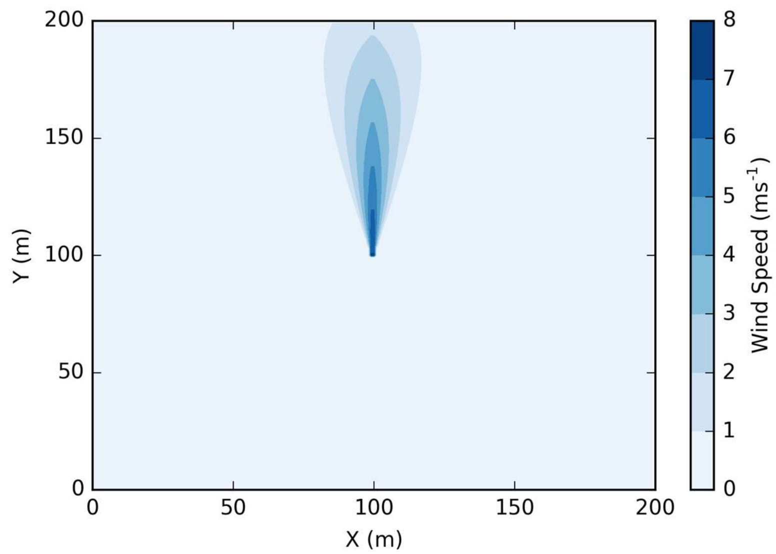


Figure 2.1. Estimated wind speed around a 124 kW frost fighting machine located at (100, 100) (after Riberio et al., 2010).

Although vertical flow wind machines require lower energy inputs, an evaluation of a 6.3 kW installation (operated over 1 hectare), found very small (< 0.3 °C) increases in 1.5 m temperature under strong inversion conditions and no benefit under weak inversion conditions (Battany, 2012). Battany (2012) also conducted smoke flow tests on vertical flow wind machines and found that the smoke rose to 25 m and then slowly dispersed and settled, indicating that these machines have little influence on the inversion.

2.2.2. Helicopters

Helicopters are used in frost fighting applications in a similar manner to wind machines. They do not have installation costs, but are substantially more expensive to operate. Therefore, helicopters are most often used in situations where frost fighting is rarely otherwise needed. Typically, one helicopter is used to cover between 22 to 44 hectares depending on the size and weight of the helicopter. Overpasses are required every 30 to 60 minutes at heights of 20 to 30 m (Snyder et al., 2005). Hovering helicopters commonly increase the surface temperature by a much larger amount than wind machines (3 to 4.5 °C; Snyder et al., 2005), indicating they are more effective at breaking an inversion. For the purpose of routinely and systematically decreasing PM10 concentrations using helicopters they would need to be used at least nightly and possibly more frequently. Helicopters are significantly more hazardous to operate than wind machines - Civil Aviation Authority regulation 91.311 precludes Visual Flight Rule (VFR) flights (excluding takeoff and landing) below 1000 ft over populated areas. We have therefore not given further consideration to the use of helicopters for PM10 dispersion.

2.3. Enhancing the effects of the low level jet

As discussed above, the most likely mechanism underlying the observed mid-evening decrease in PM10 concentrations is a low level jet wind that generates additional turbulence in the SBL and advects clean air into layers of the atmosphere overlying the SBL. Price (2014) observed a weak low level jet between 50 and 130 m above the surface with wind speeds of 1.8 to 4 m s^{-1} (mean 3 m s^{-1}). While it is uncertain to what extent augmenting this low level jet using a large horizontal flow fan situated in the jet core would be possible from an engineering standpoint, we assess the potential impacts of doing so on PM10 concentrations through dispersion modelling in Section 3.

2.4. Drawing air down the Clutha River drainage

As detailed in Section 1.1, because of local warming of surface air by the warmer Clutha River water, and the narrowness of the Roxburgh Gorge, it is unlikely that the Clutha River drainage also drains polluted air from the Alexandra basin. It is conceivable that increasing air flow down the Clutha River could decrease PM10 concentrations by exporting polluted air down the river. The cross-sectional area of the gorge in the vicinity of the Air Zone boundary is 12,000 m^2. In section 3 we model the effects of increasing drainage down the Clutha River. It is important to recognize, however, that there is no precedent for this sort of intervention and the physical feasibility has not been characterized here as it is beyond the scope of this report.

2.5. Other methods to reduce PM10 concentrations

While a detailed literature review did not provide any examples of modifying SBL stability conditions to reduce air pollution levels, several other novel interventions were found in the literature and we briefly discuss these approaches and bring them to the attention of the council.

2.5.1. Trees for passive PM10 removal

Increased tree plantings have been shown to reduce PM10 concentrations. Trees have a greater leaf area than other vegetation on which PM10 can be absorbed and also create more turbulent mixing as wind blows over the trees which increases settling velocities and net PM10 deposition (Beckett et al., 2000). A number of studies have shown modest reductions (e.g. about 10%) in the annual average PM10 concentration dependant on the amount increased tree cover. It is also possible to model the effects of increased tree cover on annual average PM10 concentrations (e.g. Tallis et al, 2011; Silli et al, 2015; Mcdonald et al, 2007). While the addition of trees may lower average PM10 concentrations, this intervention may not be as effective at alleviating peak concentrations. The settling velocity of PM10 onto trees, and thus the amount of PM10 removed, significantly decreases with decreasing wind speed (Freer-Smith et al., 2004; Beckett et al., 2000). PM10 concentrations are often elevated because of temperature inversions, which are associated with calm clear conditions; as such the effectiveness of trees in reducing PM10 concentrations under inversion conditions would likely be minimal.

2.5.2. Domestic scale electrostatic precipitation

Electrostatic Precipitators (EP) are used to remove PM10 from flue gases after combustion, but before it is emitted from a chimney or stack. EPs remove PM10 from waste gas by first inducing an electrostatic charge in the PM10 particles and then uses the charge to attract the particles to an oppositely charged surface. When enough particles have precipitated onto the surface it must be cleaned. Although, EPs are frequently used in large-scale industrial settings, there have recently been attempts to downscale EPs to house-scale to reduce PM10 emissions from domestic wood-fired heating. These technologies are still under development, but early results show at least a 75% reduction in PM10 emissions (Rada et al., 2012). The status of these devices is currently unclear, but if developed to be commercially viable, they could provide a significant reduction in PM10 loading of the SBL without the need to remove existing wood-burners.

3 Dispersion of airborne particulate matter

To assess the effect of boundary layer interventions on PM10 concentrations, a tailored vertical dispersion model was developed for this project based on a numerical solution to the advection-diffusion equation that describes the key processes controlling PM10 dispersion (Qian and Venkatram, 2011). The model treats the urban area as a single spatial unit disaggregated into a number of vertical model levels, typically 1 metre apart, and assumes horizontal homogeneity of meteorology and PM10 emissions in each layer. The model runs forward in time, allowing PM10 released at a prescribed rate to disperse vertically according to characteristic atmospheric profiles. A detailed description of the model is given in Appendix B but a short description is given here.

For each model level, the change in PM10 concentration with time is a function of:

- The vertical flux of PM10, which varies according to the vertical diffusivity (K) and the vertical gradient of PM10.
- The advection of PM10 by wind out of a control volume overlying the town area.
- The rate of emissions, which varies on an hourly basis.
- The deposition of PM10 to the surface, which varies by the concentration in the lowest model level and a characteristic deposition velocity.

Horizontal dispersion and advection of PM10 are important processes to consider if one wishes to correctly model the spatial patterns of PM10 concentration, particularly at the edges of urban areas. However, as our goal is to understand the effect of interventions on characteristic mean conditions these processes are of less importance and we have chosen here to exclude these processes.

Three characteristic profiles of diffusivity were created for nighttime, transition and daytime periods based on measurements of atmospheric turbulence in Alexandra (Price, 2014). To capture the observed mid-evening dip in PM10 concentrations in the baseline scenario, a low level jet is introduced into the model, which increases the diffusivity below 40 m by 1.5 times and from 40 m to 150 m by 10 times. Furthermore, the jet introduces additional advection of clean air into the upper layer.

Figure 3.1 shows the good match between observed PM10 (daily mean 75.0 $\mu g\ m^{-3}$) and modelled PM10 (daily mean 74.3 $\mu g\ m^{-3}$). Daytime values are lower than observed but this is not concerning as daytime periods contribute less to the daily average. A temporally varying diffusivity profile would likely increase model performance.

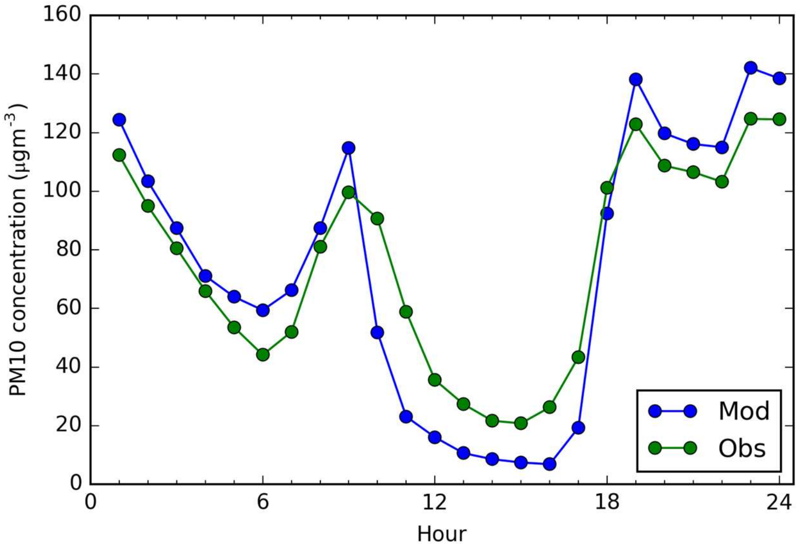


Figure 3.1 Modelled PM10 concentration compared to average daily cycle of PM10 on high pollution days.

Figure 3.2 shows the variation of PM10 with height through the same 24 hour period. It is notable that moderate PM10 concentrations exist at 10's of metres above the surface. The effect of the low level jet is evident during the mid evening.

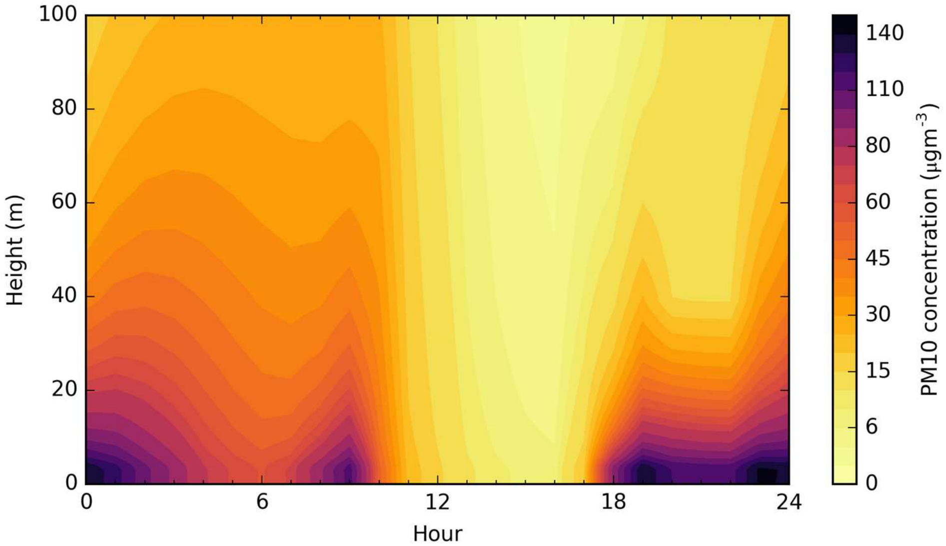


Figure 3.2 Modelled PM10 concentration with height over 24 hour period.

Measurements of PM10 at two levels can be used as a first step to validate the model's ability to simulate vertical profiles of PM10. During selected days in a period from late Autumn and early Winter, the mean value of PM10 at 4 m was 33.6 μg m^{-3}, while at 26 m was 23.2μg m^{-3} (Ancelet, 2013). Hence, on average PM10 values at 26 m height are approximately 69% of the 'surface' concentrations'. In the model output here, concentrations at 25 m are 49% those at 3 m (25 - 75%

during the nighttime), indicating the vertical profile is adequately reproduced (Fig. 3.3). Most of the deviation is during the period the low level jet is simulated, and it is expected the variations in diffusivity with height would nuance this profile.

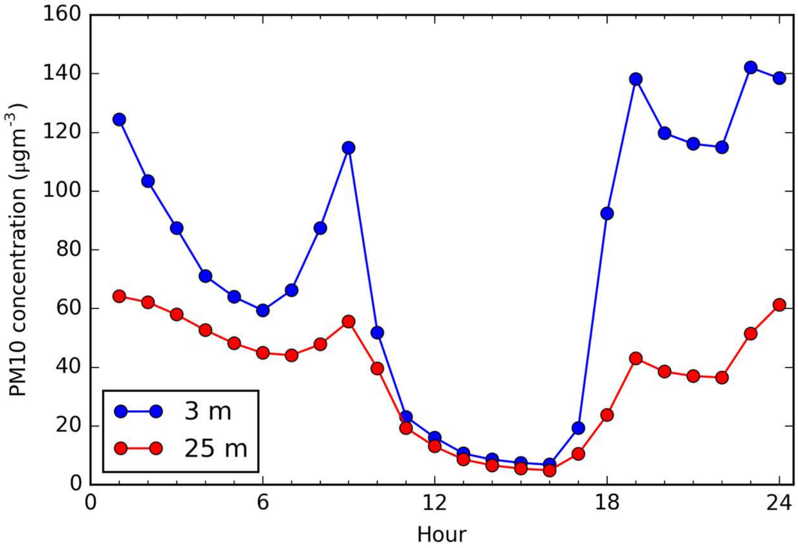


Figure 3.3 Modelled PM10 concentration at 3 metres and 25 metres height over 24 hour period.

Figure 3.4 schematically summarises the effect of the low level jet wind on PM10 concentration. Without the jet, limited diffusion occurs as mixing is limited within the SBL and little horizontal transport of PM10 occurs in/out of the shallow depression in which the Alexandra township sits. The jet lowers PM10 by advecting cleaner air over the township and increases the mixing of this clean air with the highly polluted air close to the surface.

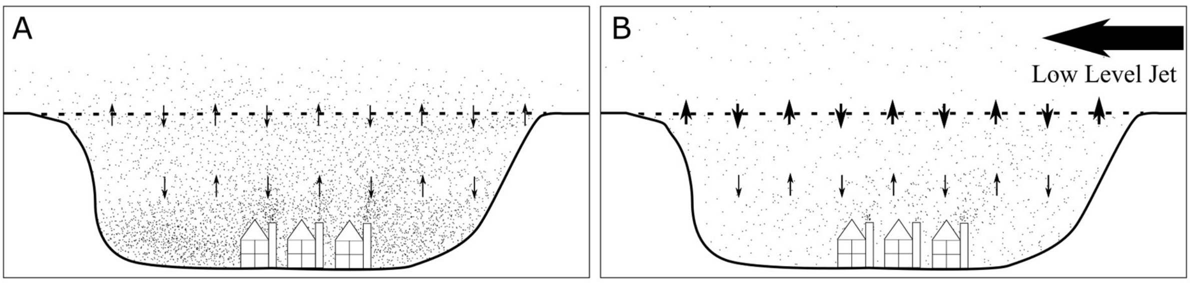
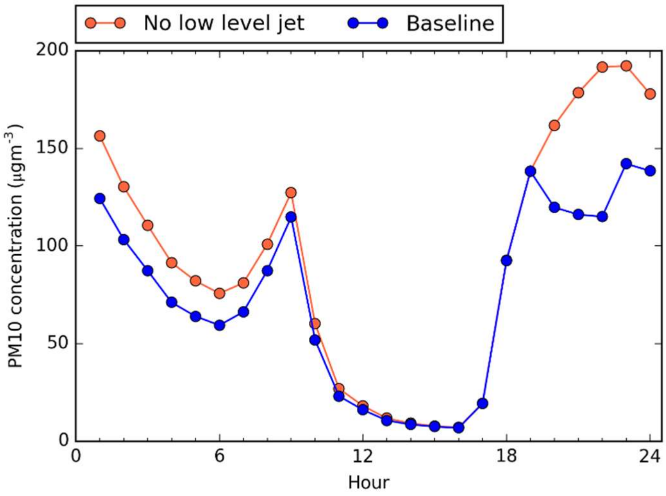


Figure 3.4 Schematic showing dispersal of PM10 from the Alex without (A) and with (B) the low level jet wind aloft.

Model runs with no low level jet show that the daily average concentrations would likely be 25% higher (mean value 94 μg m^{-3}) than currently experienced (Fig. 3.5).



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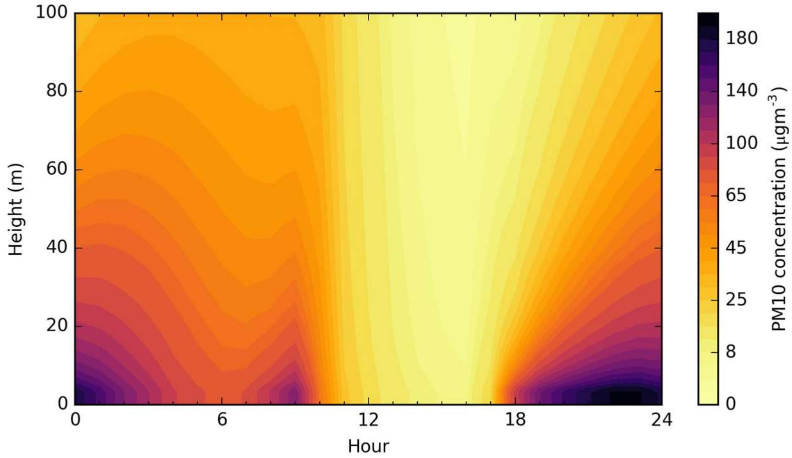

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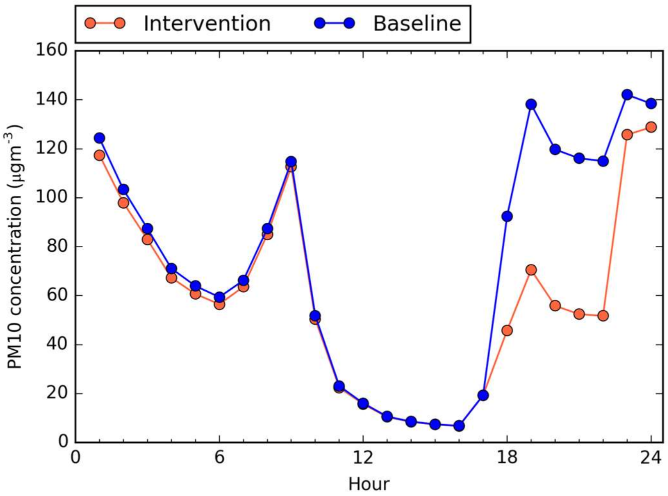
Figure 3.5 Daily cycle of PM10 concentrations in simulations with no low level jet present. Panel A shows modelled PM10 at 3 m against the baseline simulation, while panel B shows modelled PM10 in the lowest 100 m.

3.1. Effect of wind machines on dispersion

To simulate the effect of frost fighting fans on PM10 concentrations, the diffusivity in the lowest model levels (<= 21 m) was increased. Even with extremely large increase in diffusivity (× 10), the decrease in PM10 concentration is only moderate, with approximately 50% reduction during operation (Table 3.1 and Figure 3.6). The effect is also short lived with PM10 concentrations quickly climbing back to high levels once the intervention ceases at 10pm (Figure 3.6). With a more realistic increase in diffusivity (× 2) the effect is very moderate (Table 3.1). If the fans were run all night a decrease of only 22% is indicated (Figure 3.7).



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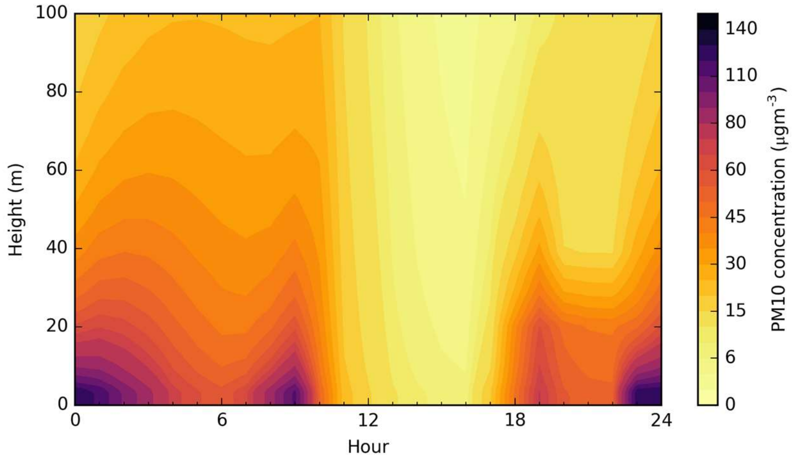

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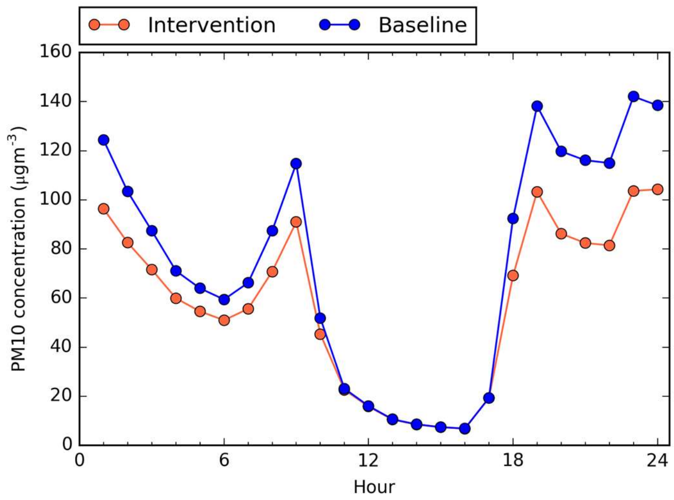
Figure 3.6 Daily cycle of PM10 concentrations with fan intervention from 1700 to 2200 h (K × 10). Panel A shows modelled PM10 at 3 m against the baseline simulation, while panel B shows modelled PM10 in the lowest 100 m.

Table 3.1 Percentage change in daily mean PM10 (μg m^{-3}) from baseline for intervention scenarios

Period of operation	Increase in diffusivity (*K*)	% change in daily mean PM10 from baseline
1700 to 2200 h	*K* × 10	-20.6%
1700 to 2200 h	*K* × 2	-10.6%
All night	*K* × 10	-40.5%
All night	*K* × 2	-21.5%



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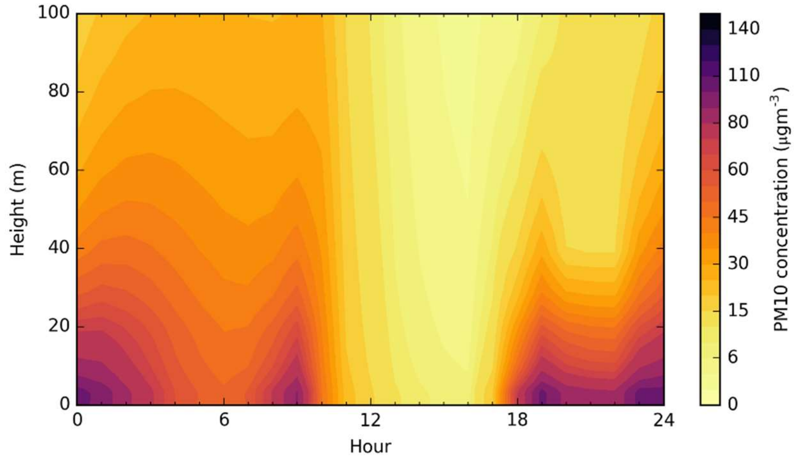
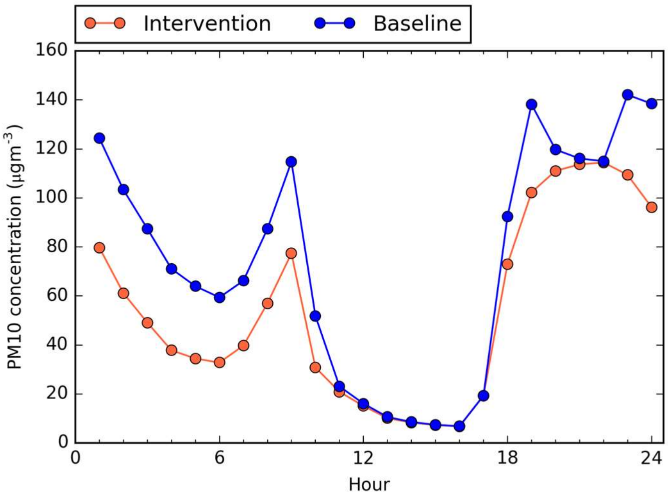


B

Figure 3.7 Daily cycle of PM10 concentrations with realistic fan intervention (K × 2) all night. Panel A shows modelled PM10 at 3 m against the baseline simulation, while panel B shows modelled PM10 in the lowest 100 m.

3.2. Effect of emulating the low level jet

If it were possible to emulate the effect of the low level jet through the entire period of stable conditions (1700 to 1000 h) the mean daily concentration would be reduced by 27%.



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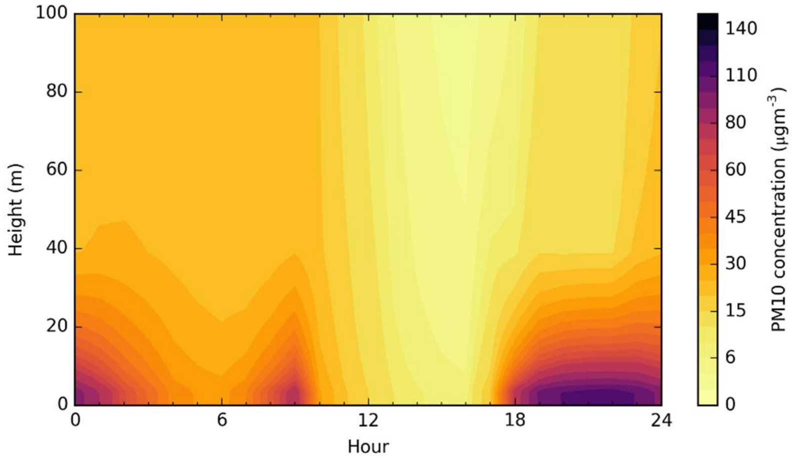
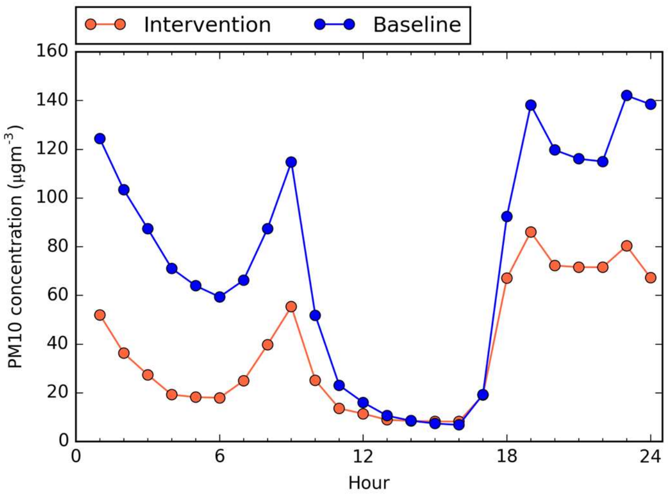


B

Figure 3.8 Daily cycle of PM10 concentrations with low level jet style intervention continuously from 1700 h to 1000 h. Panel A shows modelled PM10 at 3 m against the baseline simulation, while panel B shows modelled PM10 in the lowest 100 m.

3.3. Effect of drawing air down the Clutha River drainage

If it were possible to draw air down the Roxburgh Gorge, the effect on PM10 concentrations would depend on both the rate of airflow and the effective area the airflow would draw from. If the scheme only drew air from the area requiring intervention (230 ha; see Fig. 4.1), a 3 m s^{-1} (11 km h^{-1}) wind would be required to reduce PM10 concentrations by 50%. The gorge pump would likely draw air from a much larger area and here we use the area of the Air Zone (830 ha) to give some reference for a more realistic area of draw. With this more realistic area, an airflow rate of around 11 m s^{-1} (40 km h^{-1}) would be required to reduce PM10 concentrations by 50%.



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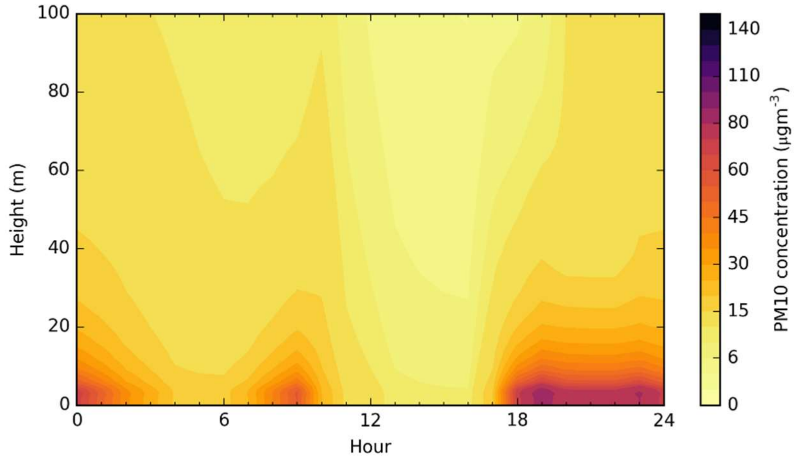

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Figure 3.9 Daily cycle of PM10 concentrations with continuous Roxburgh Gorge draw intervention over 230 ha at 3 m s^{-1}. Panel A shows modelled PM10 at 3 m against the baseline simulation, while panel B shows modelled PM10 in the lowest 100 m.

Table 3.2 Reduction in daily mean PM10 concentrations (%) for continuous Roxburgh Gorge draw intervention at various rates and for two different draw areas.

Wind speed (m s^{-1})	Draw area of 230 ha	Draw area of 830 ha
1	-30.3%	-12.1%
2	-42.1%	-20.7%
3	-49.0%	-26.9%
4	-53.6%	-31.6%
5	-56.9%	-35.4%

4 Feasibility of interventions on town scale

In order to estimate the feasibility of the different intervention options at a town scale, an estimate of the energy requirements is provided in this section. The engineering specifications are beyond scope of the current report and only the rough requirements of interventions are provided. In order to give context for the scale of the interventions, it is useful to firstly consider the magnitude of the energy fluxes forming the inversion, the energy contained in the inversion, and the heating output of the wood burners in Alexandra.

Estimates from Wilton (2006) and Smith, Kostadinov, I. (2015) put the number of wood burners within Alexandra between 870 - 980. At a nominal heat output of 20 kW for each burner, this would equate to an aggregate heating requirement from wood burners of approximately 17 to 20 MW for the entire town. This figures provides a guide for an upper limit on the reasonable energy requirements of intervention schemes. Above this figure it would be more economically efficient to replace all wood burners with resistive electrical heating and use the energy to heat houses instead. This would remove the emission source and reduce concentrations to within the NESAQ.

4.1. Area of Alexandra likely to require intervention

In the absence of detailed emission mapping, the area of Alexandra which would require intervention is uncertain. The Alexandra Air Zone is 830 ha in area, but of that only a portion of the Air Zone contains concentrated domestic dwelling. We have excluded the area of domestic dwellings on Bridge Hill as it is expected that the naturally sloping site will encourage the advection of PM10 downhill out of the area of dwellings. The total area of concentrated domestic dwellings sited on the flat area of Alexandra has been mapped as approximately 230 ha (Figure 4.1).

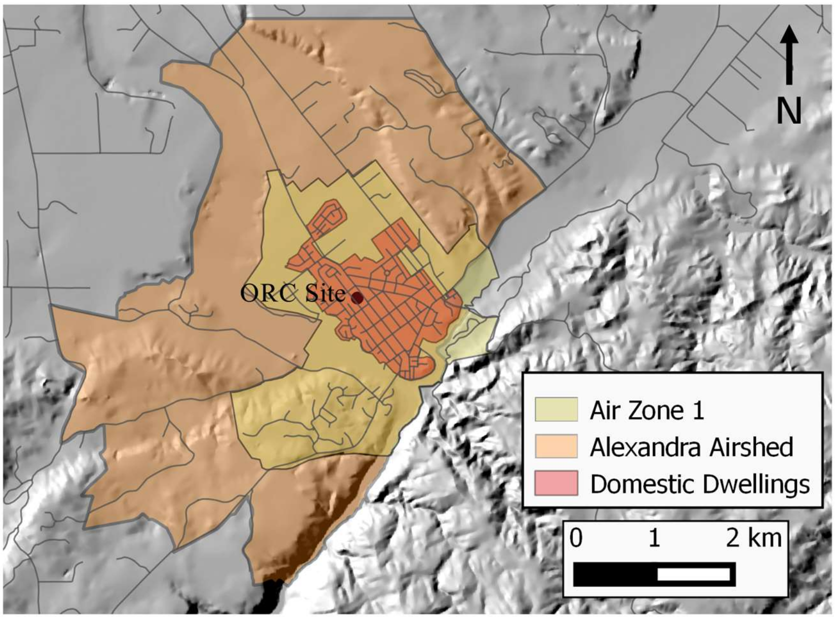

Fig. 4.1. A map detailing the area of concentrated domestic dwellings on the flat area of Alexandra.

4.2. Magnitude of energy fluxes creating inversion

The energy creating the inversion is primarily the loss of longwave radiation from the surface. No measurements of this value are available for Alexandra, but typical wintertime radiative loss for suburban areas in Christchurch is 50 W m^{-2} (Spronken-Smith et al., 2006). Considering only the limited area requiring intervention (230 ha), 115 MW of energy is involved in creating the inversion. The estimated radiative loss across the Air Zone (415 MW) is comparable with the capacity of the Clyde Dam. While these values are clearly exceptionally large, they provide a conceptualization of how powerful the forces forming the temperature inversion are.

Another way to conceptualise the inversion is to calculate the energy required to lift a parcel of air from the surface to the top of the inversion layer, the Convective Inhibition (CIN). The CIN is equivalent to negative values of convective potential energy which is a measure of the buoyant force contained in summertime convective thermals. CIN is calculated by:

$$CIN = g \times \left(\left(T_{v\,parcel} - T_{v\,env}\right)/T_{v\,env}\right) \times dz$$

Where $T_{v\,parcel}$ is the virtual temperature of the parcel of air and $T_{v\,env}$ is the environmental virtual temperature (the temperature the air would be without an inversion), g is the acceleration due to gravity and dz is the depth of the layer (AMS, 2016). Units are J kg^{-1}

For an inversion layer 50 m deep and an inversion strength of 1 °C, CIN is 1.312 J kg^{-1} assuming an environmental lapse rate of 0.010 °C m^{-1}. For an inversion strength of 2 and 3 °C, CIN is 2.21 and 3.11 J kg^{-1}, respectively. The density of air is 1.25 kg m^{-3}, so for an area of 2,300,000 m^{-2} by 50 m, the total CIN is 189 MJ for 1 °C, 318 MJ for 2 °C and 447 MJ for 3 °C inversions, respectively.

4.3. Wind Machines

If wind machines were employed to modify the inversion and increase PM10 dispersion, they would be need to be installed across the entire area needing intervention. The results of the dispersion model assumed a density of 1 machine per 4 ha, which equates to a total of 58 machines for the area of Alexandra. At a shaft power of 118 kW per engine this would equate to c. 6.8 MW of energy to create the moderate effects seen in the dispersion modelling on a town scale.

There are several complications to the use of wind machines for PM10 intervention. Wind machines are not able to operate in supercooled fog as there is the potential for severe damage to the machine due to ice buildup on the blades. This could limit operation on cold nights, which typically lead to high PM10 concentrations. In addition, because wind machines have only been investigated for use in agricultural settings, it is uncertain how effective wind machines would be at modifying inversion characteristics in the complex surface environment of an urban area. Finally, operational noise of wind machines can be a significant problem with the consenting process (Snyder et al., 2005).

In summary, the use of frost fighting wind machines would be unlikely to succeed in reducing PM10 concentrations to meet the NESAQ. The energy requirements are large, the effect on the inversion small, and consequently the effect on PM10 dispersion is limited. If a higher density of wind machines were used, the effect on the inversion at the surface would be much greater. However, the effect of the increased diffusion would have only limited effect on surface PM10 concentrations, as significant concentrations of PM10 are still held at 10's of metres above the surface.

4.4. Emulate low level jet wind

While the engineering feasibility of reproducing or enhancing the observed low level jet is unknown, it is possible to get an estimate of the energy requirements of such a scheme by estimating the power contained in the observed jet. The formula for the Power (*P*) contained in the wind (in Watts) can be written:

$$P = 1/2 \times \rho \times A \times V^3$$

Where ρ is the density of air (1.25 kg m^{-3} at 5 °C), *A* describes the cross-sectional area (in the vertical plane) the air is flowing past (m^2) and *V* is the velocity of the wind (m s^{-1}).

The low level jet wind observed by Price (2014) had a speed of 1.8 to 4 m s^{-1} (mean of 3 m s^{-1}) and extended vertically from 50 to 130 m above the surface. For a section of this wind 1,000 m wide, *A* is 80,000 m^2 and *P* is 1.35 MW. This is only the power at a single cross section, and much of the energy created at a single point will dissipate due to friction at the surface and shearing with slower moving air in other layers. To create a wind over the entire area of Alexandra the power requirements would likely be much higher, in the order of 10s of MW. To significantly reduce PM10 concentrations, this would need to be maintained through the night while significant emissions occur.

In summary, it is unlikely that emulating the low level jet wind would be successful in reducing PM10 concentrations. The power requirements are large and the feasibility of the engineering is uncertain. Only a moderate effect on PM10 concentration is seen in the dispersion modelling.

4.5. Enhancing airflow drainage down the Clutha River drainage

Enhancing drainage down the Roxburgh Gorge has many of the same engineering uncertainties as emulating the low level jet wind. Similarly, the best estimate of the energy requirements is to consider the power contained in a wind in the gorge. The cross sectional area of the gorge South of the Alexandra Airshed is 12,000 m^2. Section 3 established a 40 km/hr wind speed would be needed to reduce PM10 concentrations by 50%, assuming a draw area of 830 ha. The power contained in this wind would be 10 MW, though similarly to the low level jet it would require significantly more power to create the wind due to the effects of friction and shear with surrounding still air.

Limitations and directions for future study

This report has made an assessment of the effect of meteorological interventions on PM10 concentrations using the best input data and modelling framework available. To realistically model the spatial patterns of PM10 concentration and dispersion across an urban area such as Alexandra, a three dimensional dispersion model such as The Air Pollution Model is needed. Were the council to pursue this avenue, further data are needed to provide robust input and validation data. These additional data would include reliable measurements of wind speed and direction at a minimum of 10 metres height at a number of points within the model domain of interest, vertical profiles of air temperature and wind speed through the surface boundary layer, and spatial measurements of PM10 concentrations. Measurements of vertical profiles of meteorological variables would also enable the a more nuanced vertical diffusivity profile to be developed as input to simpler models such as that used here.

The power requirements provided here for each intervention are basic and are intended to provide a sense for the scale of the energy requirements, rather than an assessment of the physical feasibility of the interventions from an engineering perspective. They should be treated as lower bounds on the energy requirements, rather than conservative maximum value estimates.

Summary

An assessment has been made of interventions that modify the atmospheric boundary layer to reduce PM10 concentrations during winter conditions in Central Otago. No examples of such interventions for improving air quality were found in the literature. The effect of several hypothetical schemes to modify the structure or circulation of the atmosphere in various ways, and their effects on PM10 concentrations during high-pollution nights, were assessed using an air pollution dispersion model. These schemes included using frost fighting fans, emulating a naturally occurring ‘low-level jet’ wind, and drawing air down the Clutha River gorge.

Schemes that are able to produce a measurable or substantial reduction in PM10 concentration at a town scale on the order of 10 MW or more. Even given these large energy inputs, the interventions are unlikely to be successful as they would need to be run continuously during periods of strong inversions and resultant periods of limited dispersion - conditions typical of Alexandra winter nights. No intervention is able to remove the inversion, which is the fundamental control on PM10 concentrations. Furthermore, the engineering requirements are highly uncertain. To reduce PM10 concentrations to levels needed to meet the National Environmental Standard for Air Quality (NESAQ), it is likely that two or more schemes would need to be run simultaneously.

No scheme is likely to succeed in reducing PM10 concentrations to consistently meet required NESAQ levels within reasonable energy input limits.

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Appendix A: Key search terms

A literature search was conducted to identify any examples of surface boundary layer modification, particularly to enhance the dispersion of PM10 associated with wood fired domestic heating. For completeness we include a list of our key search terms, combinations of which were used to search for occurrences through google searches, google scholar searches and online searches of key journals.

Active
Boundary layer
Cold air drainage
Dispersal
Dispersion
Engineering
Enhancing
Fan
Forced breakup
Forcing
Frost fighting
Geoengineering
Intervention
Intervention
Mitigation
Modification
Nocturnal stable boundary layer
PM
PM10
PM10 dispersal
PM10 dispersion
Reduction
Remediating
Surface boundary layer
Temperature inversion
Temperature inversion layers
Wind
Wood smoke
Wood smoke pm10

Appendix B: Description of vertical dispersion model used in study

To assess the effect of boundary layer interventions on PM10 concentrations, a vertical dispersion model was created based on a numerical solution to the advection diffusion equation (Qian and Venkatram, 2011). The model uses prescribed hourly PM10 emission rates and runs forward in time allowing PM10 to disperse according to characteristic atmospheric profiles. Horizontal homogeneity of emissions and metrological conditions are assumed. The change of concentration with time ($\partial C/\partial t$) at each point can be calculated from:

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial z}\left(K\,\frac{\partial C}{\partial z}\right) + C_{src} - C_{dep} - C_{adv}$$

where the first term describes the vertical diffusion of given tracer concentration (C) according to the vertical diffusivity (K) and the vertical gradient of the tracer ($\partial C/\partial z$), C_{src} is an emission source term, C_{dep} is a surface deposition term and C_{adv} is a term describing the advection of air out of the air volume overlying the town.

The emissions are introduced at 4.5 m, which is approximately the height of domestic chimneys. Values for the emissions source term C_{src} were calculated from average daily emissions rates based on Wilton (2006) and a diurnal profile that was tuned to give reasonable fit to measured concentrations. This is discussed further in the following section.

Surface deposition (C_{dep}) is calculated in the lowest model level as the product of the concentration I this level and a deposition velocity of 1.0 × 10^{-3} m s^{-1}.

During the low level jet, air is advected into/out of the layers between 50 to 150 m height, assuming the width of the town are is 1.5 km.

Model grid and initial/ boundary conditions

The model runs on a stretched grid from 1.5 m to 1000 m height above ground level. Grid spacing increases from 1.5 m in the lowest layers to 100 m above 500 m height. A background PM10 concentration of 10 g m^{-3} (Longley and Olivares, 2008) was specified as the initial and upper boundary conditions. For each scenario, the model is run for 48 hours, with the results taken from the second 24-hour period. The first 24 hours allow model concentrations to spin up and so are discarded.

Diffusivity

The primary atmospheric parameter prescribed in the model is the vertical eddy diffusivity (*K*, units of m^2 s^{-1}), hereafter referred to as diffusivity. The diffusivity describes the rate at which PM10 disperses for a given vertical gradient of PM10 concentration. It is a function of atmospheric stability, turbulence and height within the boundary layer (Qian and Venkatram, 2011) and can be written as:

$$K = k\, u_*\, z\, \phi^{-1}$$

where *k* is the von Karmen constant, taken here as 0.4, u_* is the friction velocity (m s^{-1}) which quantifies the magnitude of turbulent mixing, *z* is the height (m), and ϕ is the integrated stability function, which describes the enhancement or inhibition of mixing due to atmospheric stability.

ϕ has been calculated using the equations of Oke (1984) in stable conditions and Dyer (1974) in unstable conditions. Representative values of $u_*$and ϕ for daytime and nighttime conditions have been calculated based on measurements made in Alexandra by Price (2014). These values are listed in the Table B.1. The characteristic values are applied over set periods to create a representative diurnal profile of diffusivity (Figure B.1).

Table B.1. Characteristic values for turbulent mixing and stability used to model diffusivity during daytime, transition, and night time periods, respectively. Both stability parameters are dimensionless.

	Turbulent mixing: u_* (m/s)	Stability: z/L	Stability correction: ϕ^{-1}
Daytime (10 am to 4 pm)	0.154	-0.70	1.79
Transition (9 to 10 am, 4 to 5 pm)	0.091	0	1
Nighttime (5 pm to 9 am)	0.032	0.32	0.45

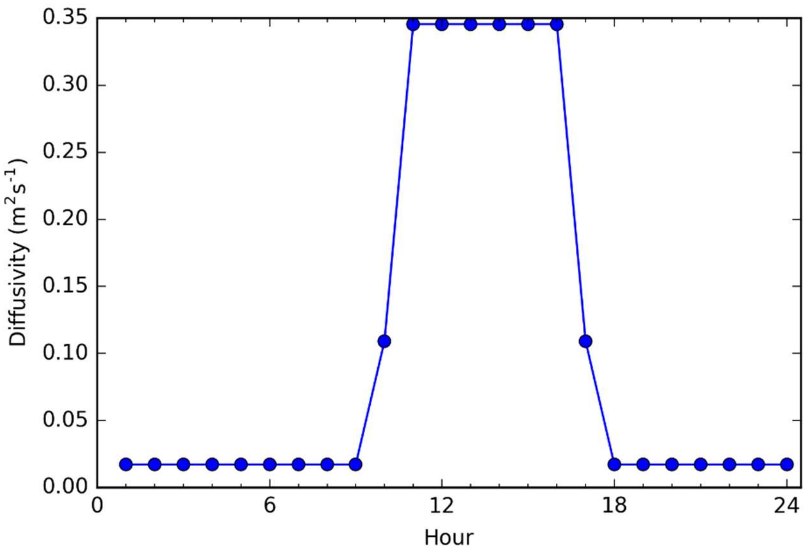

Fig. B.1. Diurnal profile of diffusivity at 1.5 m height.

To simulate the effect of the nocturnal low level jet, the diffusivity was increased in a layer between 50 m and 150 m. The wind speed peaks at around 100 m altitude above the surface but as turbulent mixing is proportional to the gradient of wind speed, the increase in diffusivity starts at 50 m. The mean wind speed in the jet was set to 3 m s^{-1}. During the jet, additional advection occurs in the same model layers (50 to 150 m). In the baseline simulations, the low level jet was introduced from 2000 h to 2200 h.

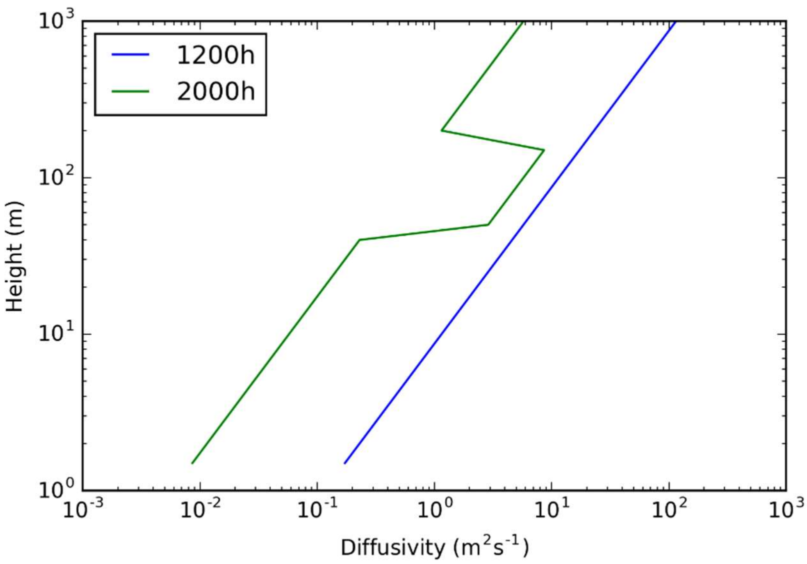

Fig. B.2. Profiles of diffusivity with height for daytime and nighttime scenarios during low level jet, respectively.

Emissions profile

As a first step in establishing the emissions profile, a daily average emissions rate of 0.448 µg s^{-1} m^{-2} was calculated using the daily total emissions (377 kg) and surface area (9.7×10^6 m^{-2}) in Wilton (2006). The diurnal pattern of emissions was established by modifying hourly emissions until a satisfactory match between the modelled and observed PM10 concentrations was achieved. The resulting emissions profile (Figure B.3) was then kept consistent for boundary layer intervention scenarios. This profile differs somewhat from that presented in Wilton (2006). Overall the emission rate (mean = 0.207 µg s^{-1} m^{-2}) is lower but is considered reasonable given the uncertainty in the emissions inventory. The Wilton (2006) estimates also have a limited temporal resolution and are based on fuel consumption instead of actual burner behaviour. Ancelet (2011) showed that burner behaviour is a critical factor in controlling emissions, and the resulting emissions profile is indicative of the predominantly use of wood burners on low burn setting that will release emissions well beyond the period the fire is stocked.

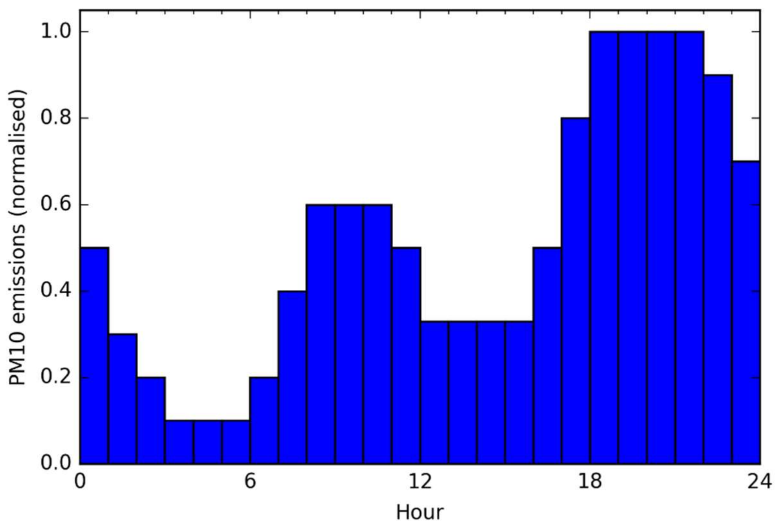

Fig. B.3. Daily cycle of PM10 emissions normalized by peak emission rate 0.400 µg s^{-1} m^{-2}.

Appendix C: List of Acronyms and Key Symbols

CBD: Central Business District
CIN: Convective Inhibition
EP: Electrostatic Precipitators
K: Vertical Diffusivity
MfE: Ministry for the Environment
MW: Megawatt
NESAQ: National Environmental Standard for Air Quality
ORC: Otago Regional Council
PM10: Particulate Matter with a diameter less than 10 µm
RL: Residual Layer
SBL: Surface Boundary Layer

Appendix D: Additional Meteorological Plots

In addition to the analysis provide in the main body of the report, we completed an analysis of data from the ORC monitoring, the NIWA monitoring station at Pioneer Park (National Climate Database agent number: 36592), and the 'Hilltop' thermometer installed on a hilltop southeast of the

Alexandra CBD (see Fig. 1.1) at an elevation 93 meters higher than the ORC monitoring. We analysed the period May to August 2009-2010 when all sites were operational. We include the figures from this analysis as supplementary material, which may be of use to the council. For each of the figures below, the hourly variability of an atmospheric parameter is plotted for the whole data set (209 days) and for exceedance days (daily mean PM10 > 50; 79 days). The hourly value at key quantiles (5^{th}, 25^{th}, 50^{th}, 75^{th}, and 95^{th}) are plotted as well as the mean.

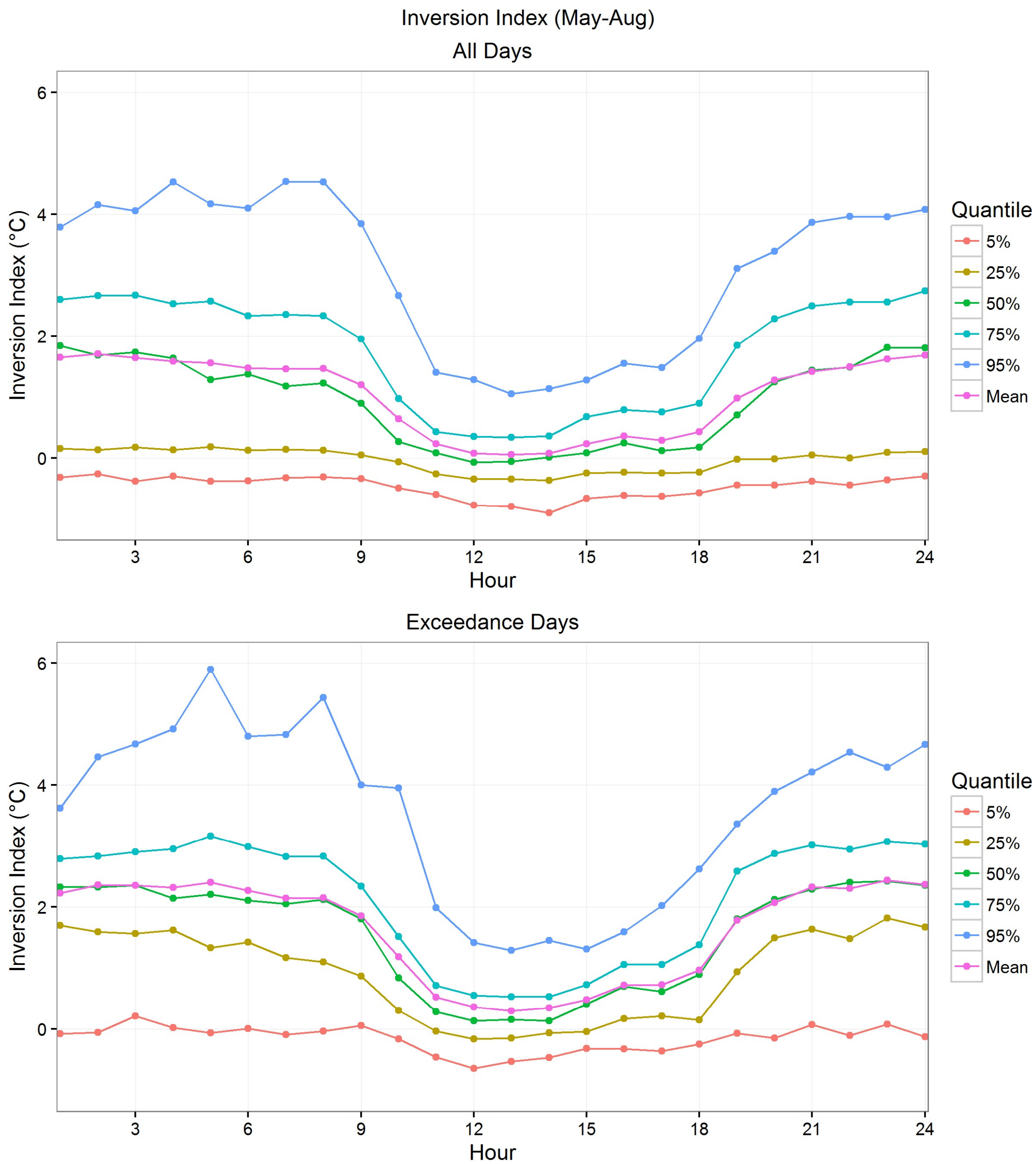

Fig. C.1 Comparison of the calculated inversion index (see section 1.1) on the whole dataset and on those days that exceed NESAQ.

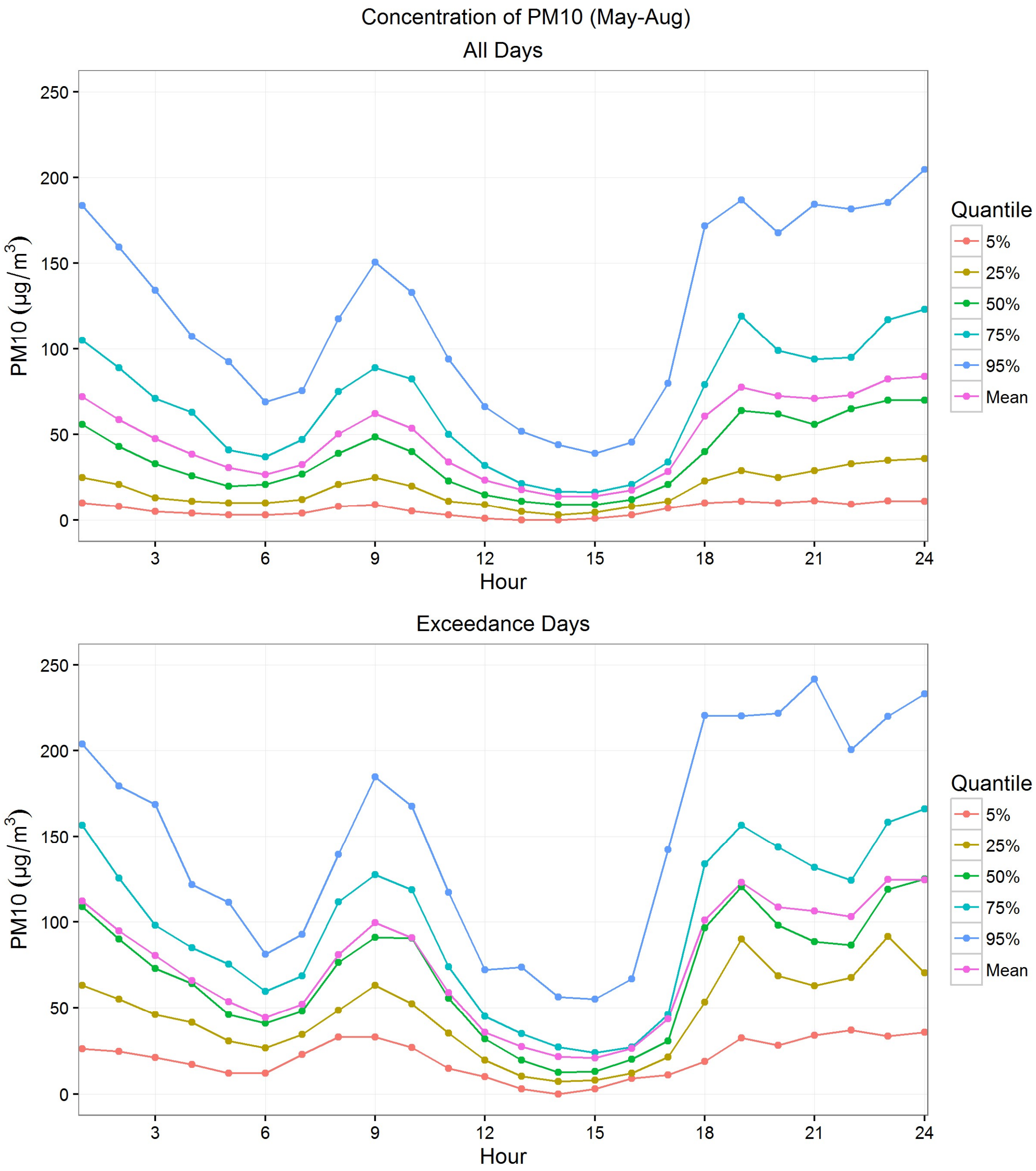

Fig. C.2 Comparison of the PM10 concentration on the whole dataset and on those days that exceed NESAQ.

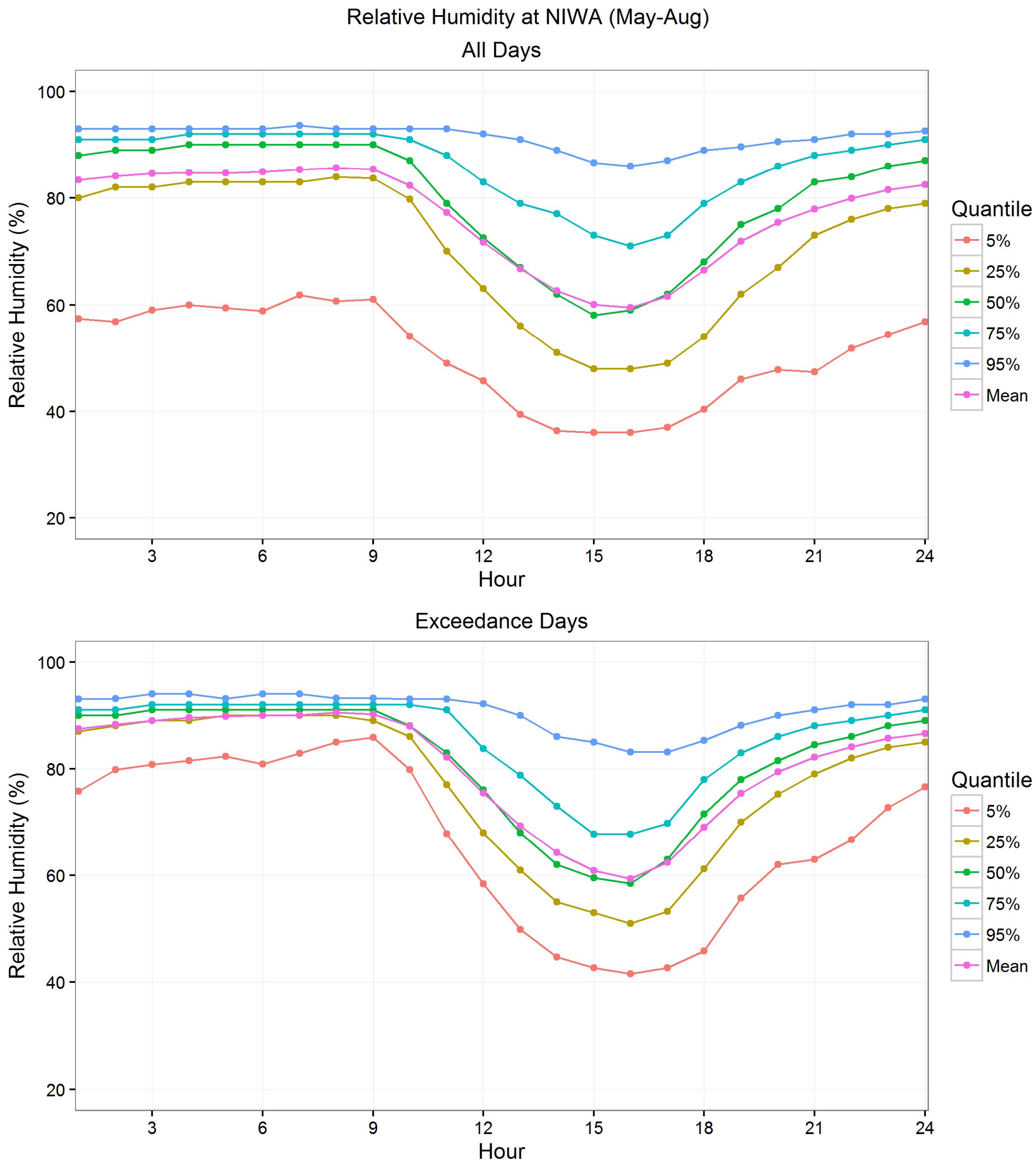

Fig. C.3 Comparison of the relative humidity on the whole dataset and on those days that exceed NESAQ, data from the NIWA climate station.

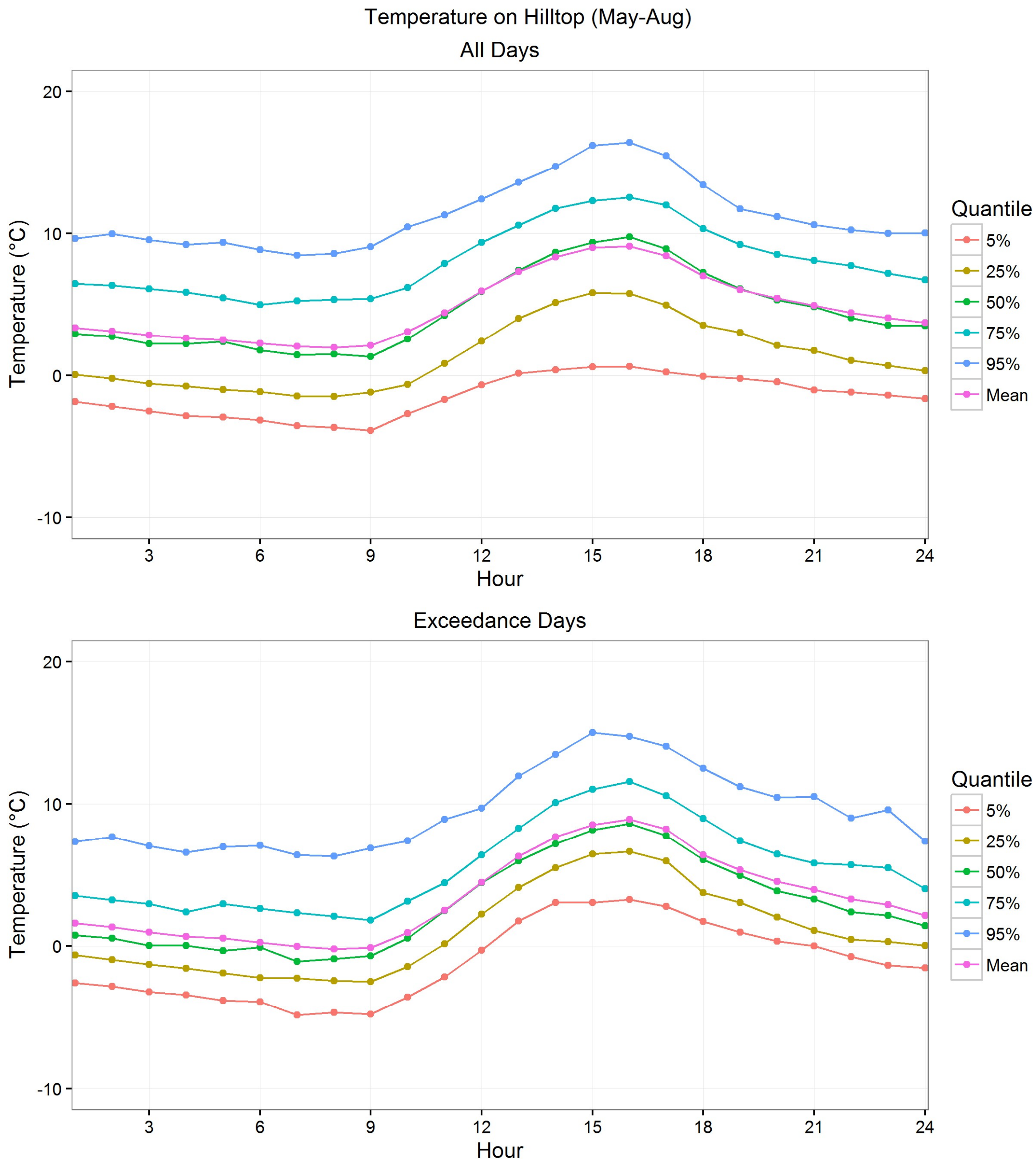

Fig. C.4 Comparison of the temperature at the hilltop Southeast of Alexandra and 93 m above the CBD (see section 1.1) on the whole dataset and on those days that exceed NESAQ.

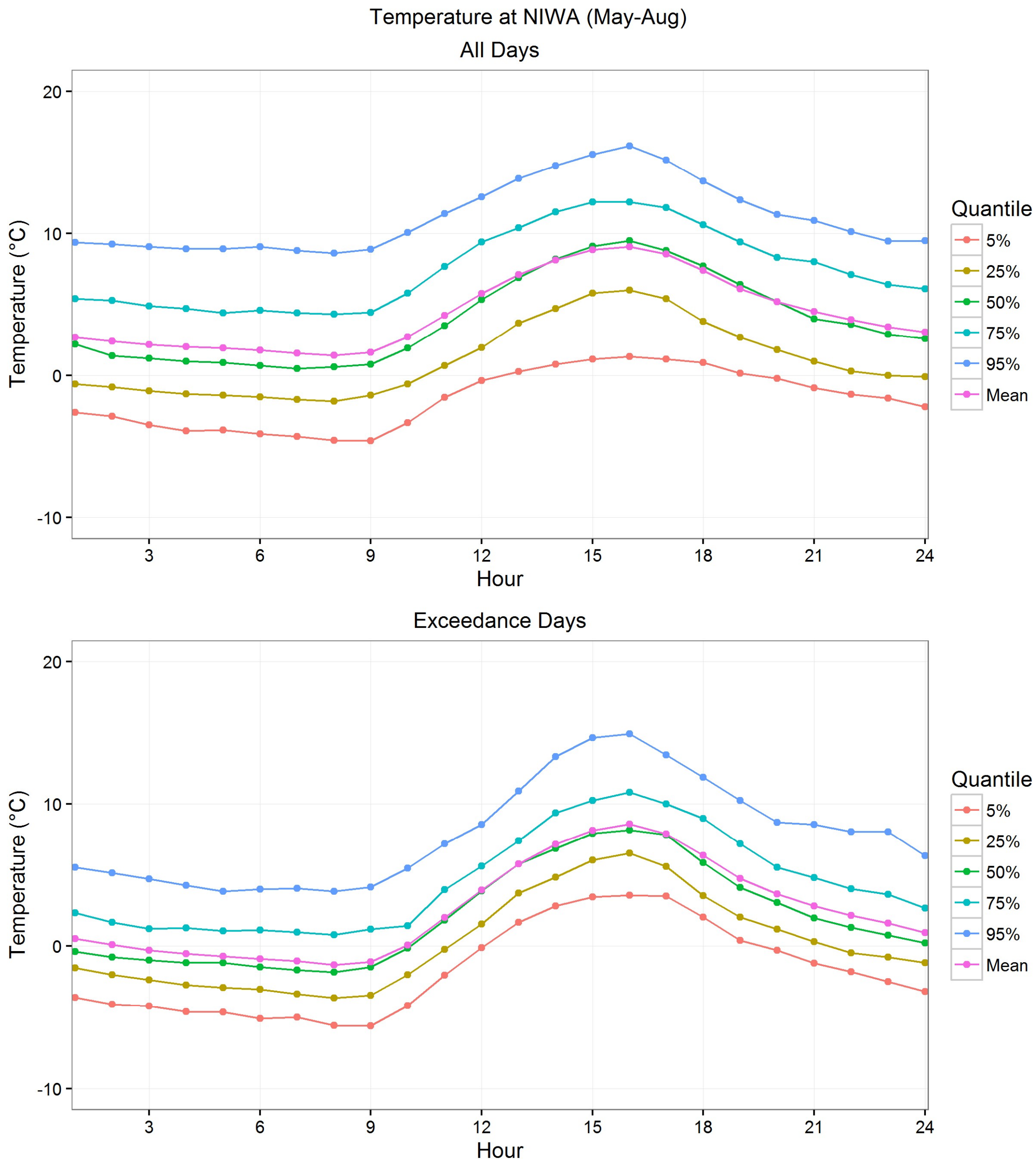

Fig. C.5 Comparison of the temperature at the NIWA climate station on the whole dataset and on those days that exceed NESAQ.

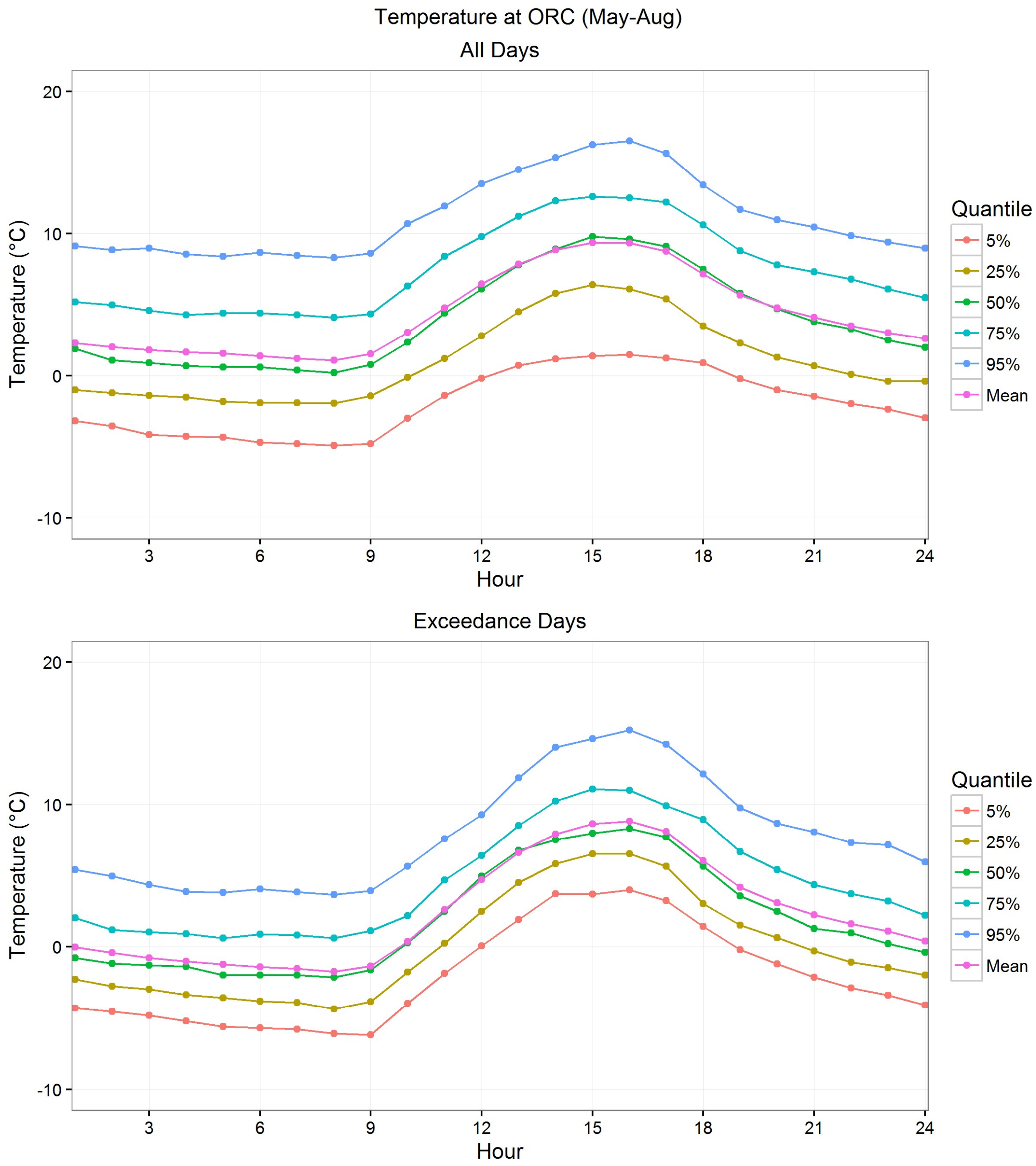

Fig. C.6 Comparison of the temperature at the ORC monitoring station on the whole dataset and on those days that exceed NESAQ.

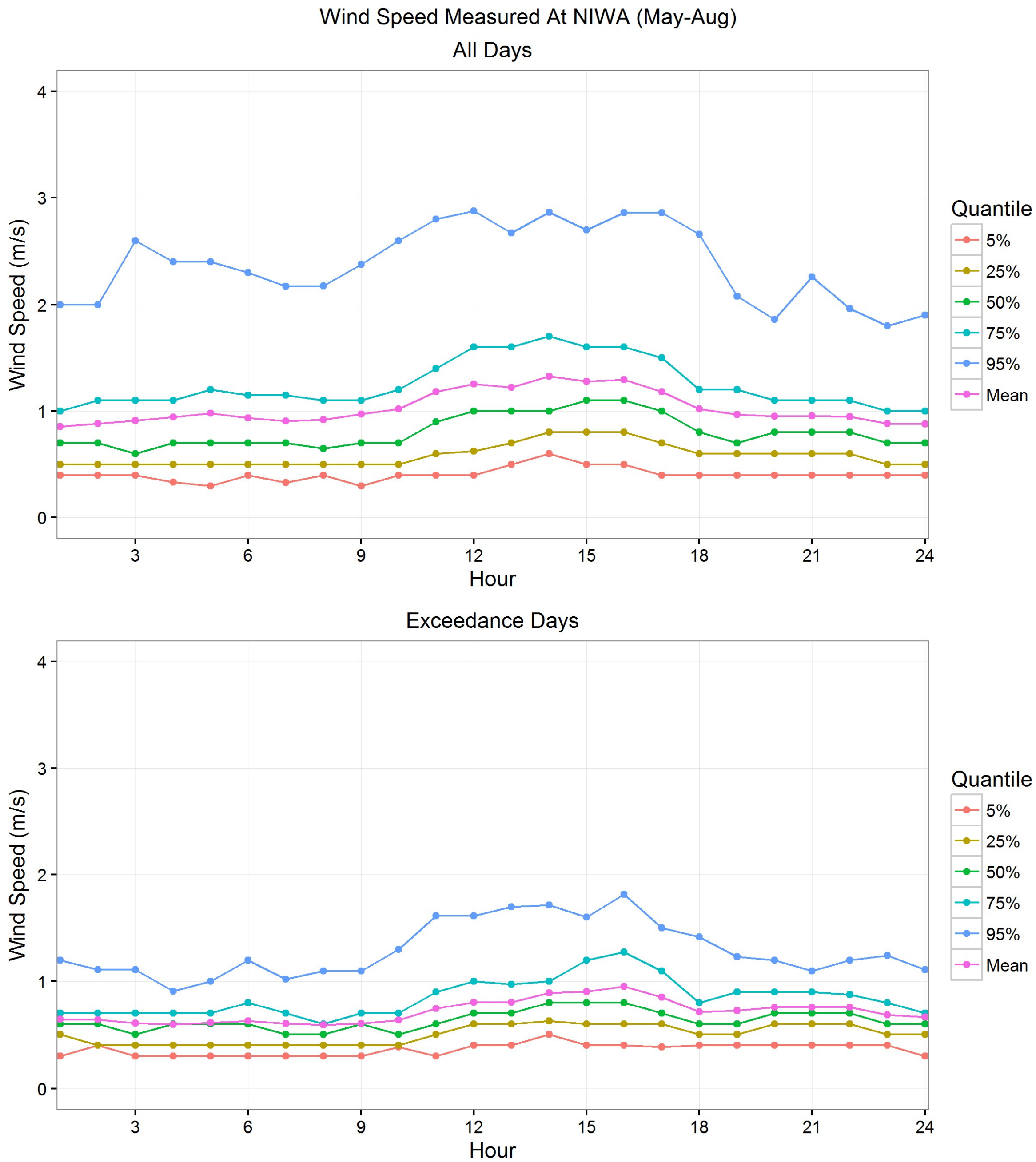

Fig. C.7 Comparison of the wind speed at the NIWA climate station on the whole dataset and on those days that exceed NESAQ.

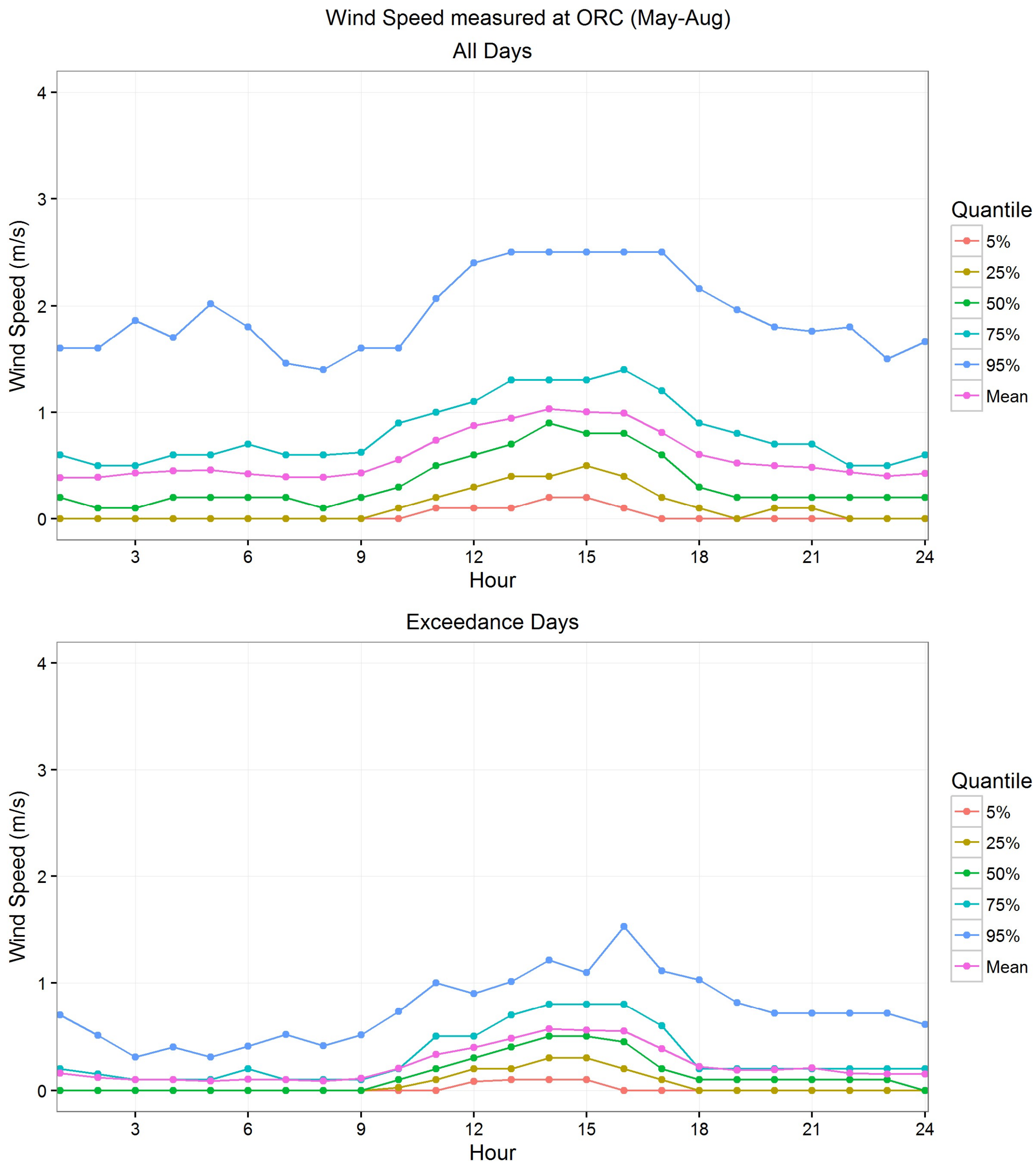

Fig. C.8 Comparison of the wind speed at the ORC monitoring station on the whole dataset and on those days that exceed NESAQ.