Investigating Ambient Air Quality in Arrowtown using ODINs (2019)

A "CONA" Progress Report

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Executive summary

Over a decade's worth of monitoring by Otago Regional Council has shown that whilst air quality in Arrowtown in summer is amongst the best anywhere in New Zealand, during winter it is amongst the worst. Whereas air quality in other towns has improved over that time, poor air quality persists in Arrowtown, and several other towns like it where solid fuel burning for home heating is common.

"Community Observation Networks for Air", or CONA, is a NIWA research initiative begun in 2015. It aims to explore how enhanced community-scale air monitoring networks, enabled by new low-cost technologies, and monitoring in the home in particular, can increase engagement with air quality issues, improve public understanding of the science, and promote or accelerate reductions in emissions or other actions to improve air quality in places like Arrowtown.

After pilot studies elsewhere, NIWA brought the CONA project to Arrowtown in 2019. This report is the first in a series covering this field study. It covers the results of an initial analysis of data from a network of prototype ambient air quality sensors ("ODINs") developed by NIWA. A companion report (Part Two) covers indoor air quality.

22 prototype ambient air quality sensors (ODINs) were deployed in a distributed grid across the town between June and mid-August. More sensors were added in August and September, reaching a maximum of 48. Although the data capture rate was moderate, sufficient high-quality data was captured to gain new insights into spatial patterns in air quality, whereas the study also provided valuable insight into instrument failures that will be used to inform future upgrades.

We draw the following conclusions with a high certainty:

- Although the official (ORC) record shows that on cold winter nights Arrowtown has some of the most polluted air in the country, exceeding National Environmental Standards multiple times per year, NIWA's network of distributed monitors has shown that air quality varies hugely across the town.

- Our data confirms that air quality during the early afternoon period is excellent at all locations.

- Persistent and predictable poor air quality is limited to cold winter nights, with a smaller, secondary impact on subsequent mornings.

- During these conditions, air quality remains generally remains good in the north-west of the town, gradually deteriorating towards the south-east. A "high risk" zone for air quality exists in an area approximately to the east of Centennial Ave and south of Boundary Street.

- At the time of writing a proposal exists to introduce a new National Environmental Standard for $PM_{2.5}$. Should that Standard be adopted, and air quality does not change, the proportion of the town that fails to meet the Standard will substantially increase compared to now, and the number of exceedances will more than double.

- Our findings to date are entirely consistent with smoke from home heating being the overwhelmingly dominant source of particulate matter in the air during winter in Arrowtown. A preliminary inspection of the data shows no evidence of a major contribution from agricultural burning, although this will be investigated further.

The following conclusions have a degree of uncertainty and will be the subject of ongoing research.

- The data captured suggests that the dominant (and maybe only) cause of the differences in air quality across the town is the gentle flow of smoke downhill and its collection in the Arrow River valley, probably driven by cold air sinking down the slopes of the adjacent hills. Alternative explanations – including higher emissions in the south-east of the town due to colder conditions, more, older, mis-used or poorly maintained wood-burners – cannot be ruled out but appear less significant.

- The monitoring technology and approach has the potential to be used to identify locations containing homes with persistently abnormally high emissions ("gross emitters") and quantify their impact. To date, one such area has been identified, and this will be the subject of further analysis.

- Results imply that actions to reduce emissions that were concentrated in the south-east of the town would be relatively more effective in reducing pollution concentrations where they are worst, reducing risk inequality and the number of exceedances of the National Environmental Standard for air quality. However, achieving the same emission reduction spread evenly across the town may be a more efficient way of reducing total exposure, and hence health risk, across the whole town.

1 Introduction

1.1 Air quality in Arrowtown

Air quality has been measured continuously in Arrowtown by Otago Regional Council (ORC) since 2006, with the monitoring site moving from Arrowtown School to Arrowtown Recreational Reserve in 2014. These measurements have shown that whilst air quality in Arrowtown in summer is amongst the best anywhere in New Zealand, during winter it is amongst the worst. Over the last decade air quality has exceeded the National Environmental Standard between 16 and 46 days per winter every year.

Studies to date have indicated that Arrowtown's poor air quality is overwhelmingly caused by emissions from burning wood for home heating. Consequently, demanding rules for woodburning appliances have been established for Arrowtown (and other towns) by Otago Regional Council. Despite this, whereas long-term improving trends in air quality are apparent in many New Zealand towns and cities over the last decade and a half, this is not so in Arrowtown where air quality has changed little in that time.

1.2 NIWA's role

NIWA (the National Institute for Water and Atmospheric Research) is a Crown Research Institute that carries out scientific research into a range of environmental topics related to water and air. It has no official role in air quality monitoring or management, but often acts as a scientific advisor.

However, NIWA does use part of the MBIE Strategic Science Investment Fund to conduct a research programme entitled "Impacts of Air Pollutants". This programme aims to help Regional Councils, agencies, businesses and the NZ public in developing understanding of air quality, expanding the scope and utility of air quality monitoring and improving the scientific evidence base for policymaking and everyday decision-making.

1.3 Community Observation Networks for Air

"Community Observation Networks for Air", or CONA, is a NIWA research initiative begun in 2015. It aims to explore how enhanced community-scale air monitoring networks, enabled by new low-cost technologies, can increase engagement with air quality issues, improve public understanding of the science, and promote or accelerate reductions in emissions or other actions to improve air quality.

Although the principles developed in CONA are designed to be applied to any air quality issue, to date the initiative has focussed on domestic home heating emissions as New Zealand's priority air quality issue. The struggle to effect real improvements in air quality in towns like Arrowtown is most likely due to financial barriers, with other political and cultural forces at work. However, a hypothesis underlying the CONA approach is that these barriers may be compounded by lack of clear evidence on effective and successful solutions, particularly for householders and owners. The CONA initiative aims to develop means to generate more localised and accessible information for the community. The aim is to better inform and motivate actions that the community can take, providing rapid feedback to evaluate and refine those actions.

The heart of the CONA initiative is a series of winter field studies in small New Zealand towns. Each study has used its host town to develop new technologies or methods, whilst simultaneously improving the understanding of air quality in that town. As CONA has developed, "daughter" projects have emerged where some of the better developed CONA technologies have been used either on a research or commercial basis (Table 1-1).

Table 1-1:   **CONA field projects to date.**

	Main CONA project	**"Daughter" projects**
2015	Rangiora	
2016	Rangiora	
2017	Rangiora	
2018	Alexandra	Gisborne, Hobart
2019	Arrowtown	Motueka, Christchurch, Kellogg (Idaho)

1.4   Scope of this report

This progress report covers the Arrowtown 2019 CONA field study. This was the first year that a CONA study was conducted in Arrowtown. It covers the results of an initial analysis of data from a network of prototype ambient (outdoor) air quality sensors ("ODINs") developed by NIWA within the 'CONA' initiative. A separate report will cover indoor air quality.

2 Arrowtown measurement campaign, 2019

2.1 Overview and goals

The Arrowtown 2019 campaign featured the following elements:

- Up to 48 prototype ambient air quality sensors (ODINs) deployed in a grid across the town to better understand variation in air quality

- 30 prototype indoor air quality sensors (HauHaus) deployed for up to 3 weeks inside 86 homes.

- Measurements of woodburner use in selected homes.

This report covers the ODINs only.

The main goals relating to the ODINs and ambient air quality were:

- Technical:

  - Test a new approach to telemetry and collection of real-time data

  - Deploy the densest ODIN network to date to enable research into spatial variation, mutual sensor validation, optimal interpolation and anomaly detection

- Local air quality:

  - Map spatio-temporal variation in air quality in Arrowtown at the maximum resolution possible with current resources

  - Gain insight into the representativeness of the ORC regulatory air quality monitor

2.2 ODINs

The Outdoor Dust Information Node (ODIN) is a low-cost air quality monitor. It is developed by NIWA and at the time of writing should be considered as an advanced prototype. The ODIN design is continually evolving and have been progressively developed and deployed through all the CONA field studies listed in Table 1-1. The version used in Arrowtown in 2019 had the following characteristics:

- Simultaneously measures particulate matter in three size ranges: PM_{10}, $PM_{2.5}$ and PM_1 (i.e. particles with an average size smaller than 10 μm, 2.5 μm and 1 μm respectively)

- Makes measurements at a user-defined time interval, usually every 1 – 5 minutes.

- Also measures air temperature and relative humidity.

- Stores data to an onboard SD card.

- Where adequate mobile phone coverage is available, data is sent immediately to a cloud server.

- Powered by a combination of solar panel and lithium-ion battery.

2.3   The Arrowtown ODIN Network 2019

The Network was deployed in four phases over winter 2019. ODINs were installed on streetlight poles as a preference (courtesy of Queenstown-Lakes District Council), with wooden power poles (courtesy of Aurora Energy) and private property also being used. The aim was to install a regular rectangular grid with even coverage across the town, insofar as available infrastructure and permissions made this possible. Table 2-1 summarises the network in each phase.

Table 2-1:   The 4 phases of the study.

Phase	Start	End	Number of ODINs installed	Average spacing between ODINs
1	29th May	2nd July	22	340 m
2	3rd July	20th Aug	22	340 m
3	21st Aug	10th Sep	37	240 m
4	11th Sep	24th Oct	47	170 m

2.4   Air quality in winter 2019 – the "official" record

ORC operate an air quality monitor in Arrowtown continuously measuring PM_{10}. The monitor is located in the Arrow River valley at the south-east corner of the town (Figure 2-1). It is used to provide an official record of air quality in the town, and whether the airshed breeches the National Environmental Standards (NES).
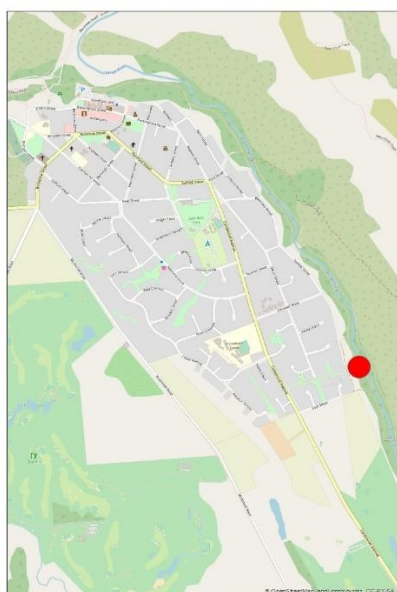
Figure 2-1:   Location of the regulatory air quality monitor operated by Otago Regional Council (ORC).

In winter 2019, the monitor recorded 20 exceedances of the NES – fewer than in the previous 5 years (ranging from 29 to 46) but more than any other location in New Zealand in 2019. The first exceedance occurred on 2nd June and the last on 18th August. High concentrations are usually associated with low winds and low temperatures that occur during anti-cyclonic conditions, which often persist for several days. Consequently, NES exceedances often occur in clusters of consecutive days. That is what happened in 2019, with all but 5 exceedances occurring in two clusters. The largest episode was in late June (10 exceedances over 13 days), with the highest concentration of 108 $\mu g\ m^{-3}$ (double the NES) on the 19th June. The second episode was in late July (5 consecutive exceedances).

One of the 20 exceedances occurred before our campaign began. 11 of the 20 exceedances occurred during phase 1 of our campaign, with the large cluster towards the end of that phase. 8 exceedances occurred during phase 2 of our campaign, with the second cluster in the middle of that phase. No exceedances occurred during phases 3 or 4 (Figure 2-2).
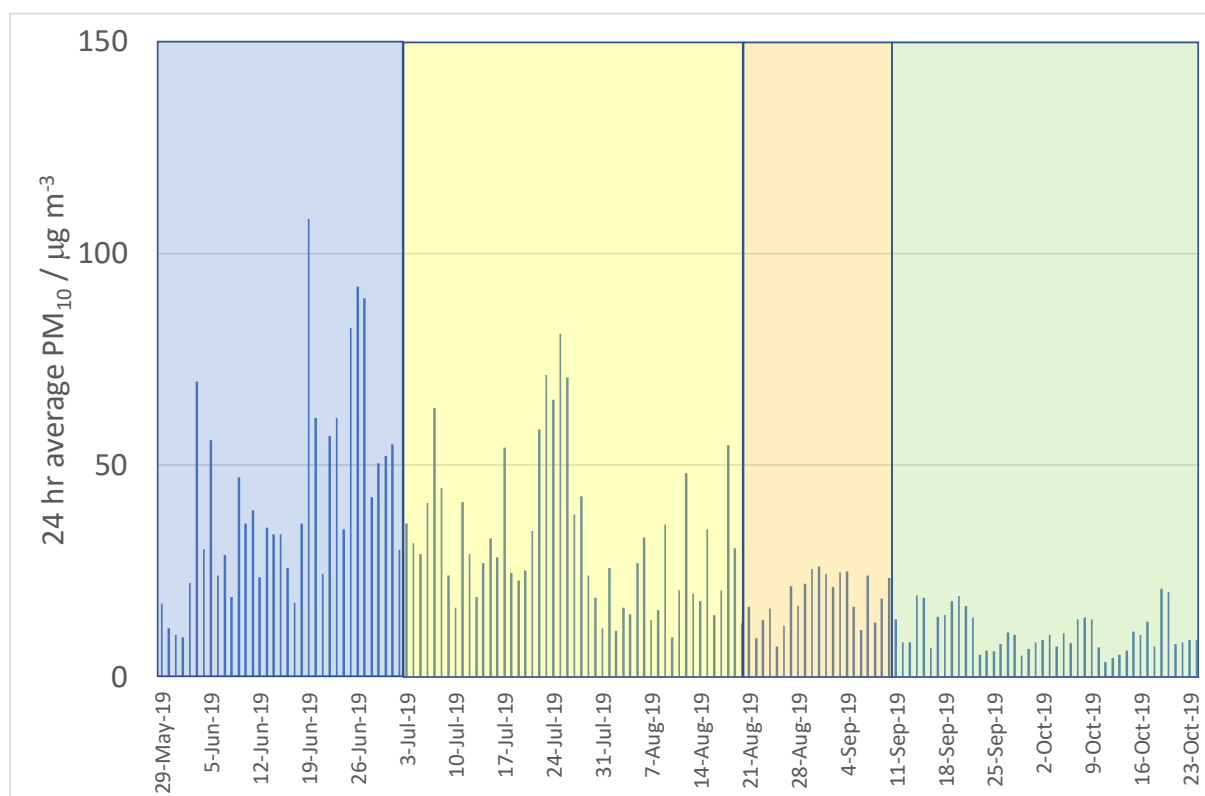
Figure 2-2:   **Daily PM$_{10}$ measured by ORC, and the four phases of this study (coloured bands).**

Table 2-2:   **Range of PM$_{10}$ concentrations (ORC) during each of the 4 phases of this study.**

Phase	24-hr average PM$_{10}$ / $\mu g\ m^{-3}$			Number of NES exceedances
	Mean	Min	max	
1	42	9	108	11

Phase	24-hr average PM$_{10}$ / μg m^{-3}			Number of NES exceedances
	Mean	Min	max	
2	32	9	81	8
3	18	7	26	0
4	11	4	21	0

3 Findings part 1 – Performance and validity of the ODINs

3.1 ODIN status and known issues

The ODIN is still a device in active development and during 2019 several upgrades were performed to the hardware, firmware and processing software. The biggest change, compared to the 2018 version of the devices, was the upgrade on the firmware that allowed it to more reliably use the GSM network for sending data to the cloud, and to recover from unsuccessful connections.

Some upgrades were made on only part of the fleet and these included more control over the telemetry options and a different communication path between the sensing element and the device controller. These upgrades were only implemented on the devices used for the final phase of the campaign.

There are a few steps in the operation of the ODIN where faults could arise that lead to data loss:

1. **Sensor fault**. On rare occasions, the dust sensor fan stops working but the device continues to communicate, in which case the ODIN reports unusually low values with little or no temporal variation. A more common fault is the ingress of a foreign object to the sensor's optical chamber, typically a spider or an insect, which results in the ODIN reporting very high values with large variations but none of the typical day/night structure. In both cases, the data is suspect and removed during the quality control process.

2. **Sensor communication fault**. On rare occasions, the sensor could fail to communicate its readings to the ODIN microcontroller, in which case the ODIN would record the value –999 which is removed during the quality control process.

3. **Internal memory fault + GSM connectivity loss.** In some cases, possibly related to overheating, the internal memory card becomes corrupted and data is no longer locally backed up. This can lead to data loss when the GSM connectivity is lost at the same time.

4. **Power failure.** The ODIN has an internal battery that allows it to operate usually for about 7 days without any re-charge. The 10W solar panel is intended to provide enough power to charge the battery fully within those 7 days. However, if the recording interval is too short (less than one minute) or the GSM signal is too low, then the power requirements of the ODIN increase and the battery is depleted much faster which leads to gaps in the data. Fortunately, once the solar panel receives enough sunlight, then the ODIN will re-start but this means that in poor GSM coverage areas it is possible that there will be data gaps between sunset and sunrise.

3.2 ODIN performance

The main failure modes during the Arrowtown winter 2019 campaign were:

- **Corrupt SD cards or other hardware faults.** This was diagnosed to be the result of aging memory cards coupled with recurrent power cycles that originated from higher than expected power consumption.

  - **Solution**: Replace the memory card.

- **Blockages or failure of the fan (rare)**. On two units, the optics chamber of the PM sensor was blocked by a spider, possibly attracted to the warm area inside the sensor. Also, on another unit, the internal fan stopped working but the cause remains unclear.

  - **Solution**: Replace the dust sensor.

- **Mismatch between the power demand of the devices and the output of the solar panel.** The most common failure was the situation where the power consumption of the unit was more than the battery and solar panel could provide. This manifested itself as data loss between dusk and dawn.

  - **Solution 1**: Re-orientate the unit to face north so that the solar panel has a clearer view of the sun.

  - **Solution 2**: Replace the battery.

  - **Solution 3**: A new firmware was developed that reduced power consumption further.

By the end of the campaign it became apparent that the current version of the ODIN was more likely to lose power if it was located at the edge or outside the town, where 2G coverage is weaker and the devices needed to provide more power to the modem to achieve connectivity. This lesson will inform future upgrades to the ODIN.

Table 3-1:   **ODIN data recovery for each phase of the study.**

Phase	Number of ODINs		
	installed	>10 % data	>90 % data
1	22	17 (77%)	10 (45%)
2	22	19 (86%)	8 (36%)
3	37	34 (92%)	26 (70%)
4	47	39 (83%)	29 (62%)

3.3   ODIN validity

3.3.1   Relationship to ORC PM$_{10}$ data

We were unable to set up an ODIN at the long-term air quality monitoring station operated by ORC this winter, so a direct comparison between ODINs and a regulatory-grade instrument was not possible. However, ODINs have been co-located with similar instruments at other locations during other projects (Alexandra, Rangiora, Christchurch, Glen Eden) with results indicating very good agreement.

Figure 3-1 shows the 24-average PM$_{10}$ from ORC for the month of July, together with 24-hr average PM$_{10}$ and PM$_{2.5}$ from the nearest ODIN (#63), located approximately 400 m away on Norfolk Street.

This figure indicates a general agreement between the ODIN and the ORC data. There is some evidence of the ODIN data having a wider range (reading higher at high concentrations and lower at low concentrations), but this might be influenced by each instrument being in different locations. It also indicates how the difference between PM_{10} and $PM_{2.5}$ is small. The difference is the contribution of "coarse" particles between 2.5μm and 10μm, most likely to be composed of mineral dust and soil.

While the ODIN is not intended to be used for regulatory compliance, we are confident that the data it creates is broadly comparable to regulatory instruments.
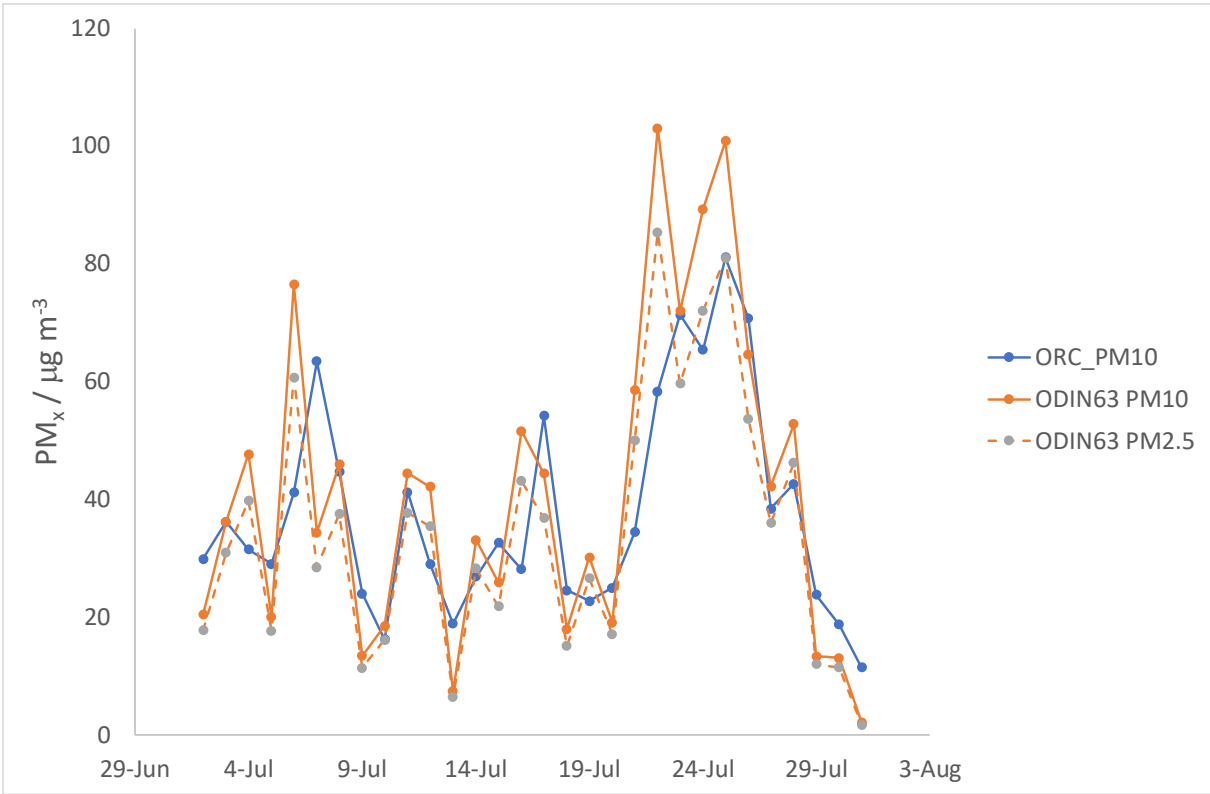
Figure 3-1:   Daily PM_{10} from the ORC monitor (blue) and PM_{10} and $PM_{2.5}$ from the nearest ODIN (#063) during July.

3.3.2   Co-location data

Whereas in previous NIWA studies, ODINs have been co-located for a period to check their response relative to each other, this was not logistically possible for the Arrowtown 2019 campaign. However, previous and concurrent studies have shown good agreement between ODINs, such that they do not typically deviate from each other by more than 20%.

As the ODIN fleet grows, however, co-location becomes a relatively inefficient means of quality control. Current and future NIWA research is aiming to develop alternative methods exploiting dense networks – i.e. each ODIN is near several others. Our primary goal is to identify instruments that are over- or under-reading.

4 Findings part 2 – Air quality in Arrowtown (winter 2019)

4.1 Temporal variation in air quality

The plot in Figure 4-1 shows the range in 24-hour concentrations (midnight to midnight) across the whole ODIN network for each day of the study during July. Figures 4-2 to 4-4 show the same for August, September and October respectively.
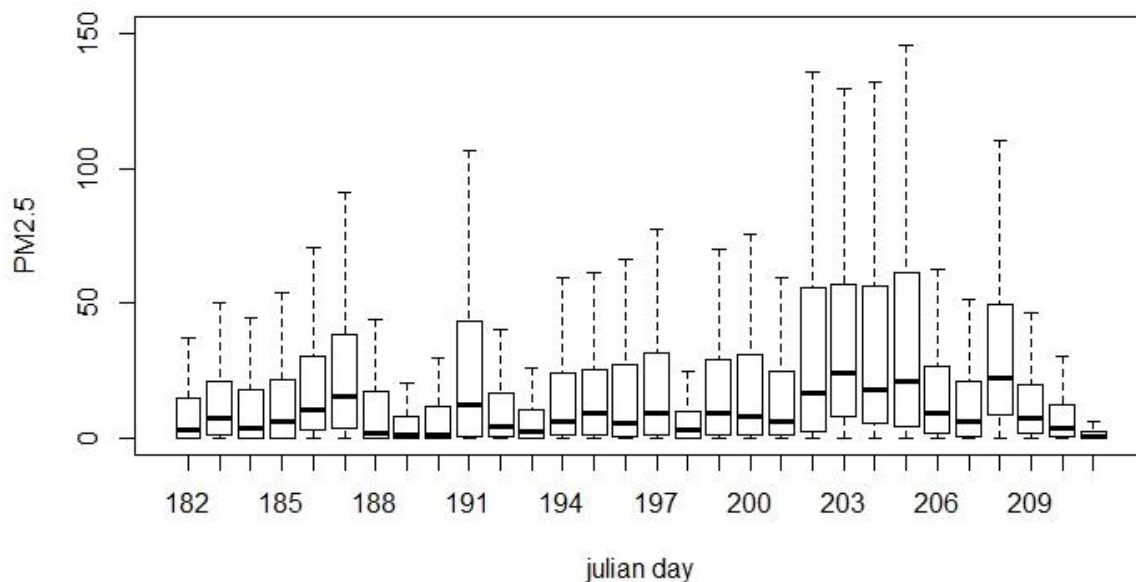
Figure 4-1: Distributions of 24 hr mean (midnight-midnight) PM$_{2.5}$ concentrations across network for each day in July.
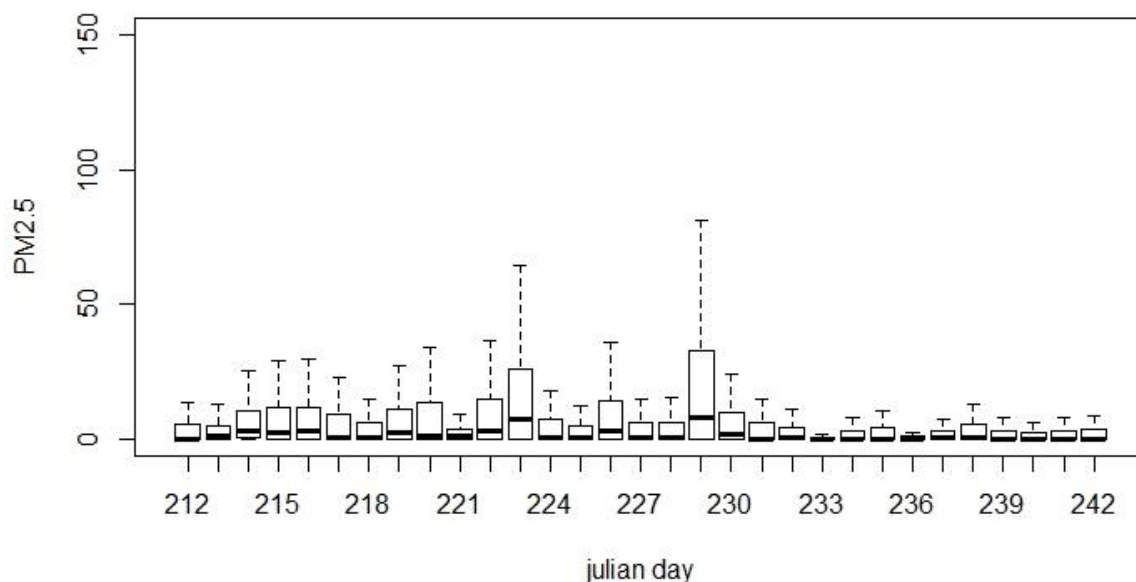
Figure 4-2: Distributions of 24 hr mean (midnight-midnight) PM$_{2.5}$ concentrations across network for each day in August.
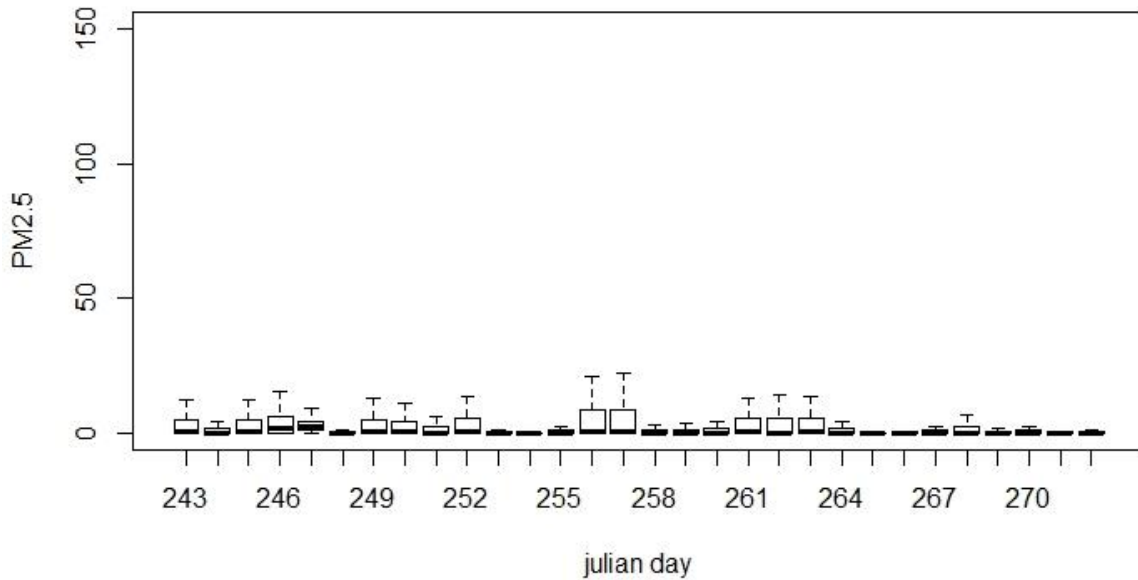
Figure 4-3: Distributions of 24 hr mean (midnight-midnight) PM$_{2.5}$ concentrations across network for each day in September.
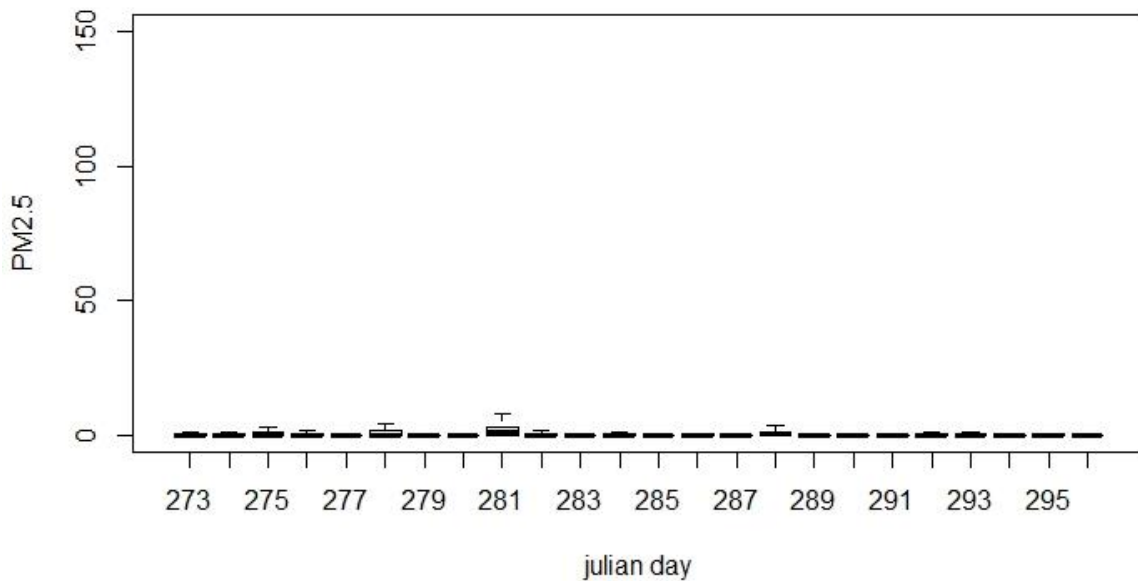
Figure 4-4: Distributions of 24 hr mean (midnight-midnight) PM$_{2.5}$ concentrations across network for each day in October.

These figures confirm that, although more ODINs were deployed in the later stages of the winter, concentrations had significantly reduced. For this reason, some of the analyses below focus only on certain phases or months of the campaign.

Figure 4-5 shows the diurnal range of concentrations across the whole network during phase 2 only. This figure shows that the data can be split into three periods:

- Night-time (4pm – 5am) – highest concentrations

- Morning (5 am – 12 noon) – intermediate concentrations

- Afternoon (12 noon – 4 pm) – consistently low concentrations.
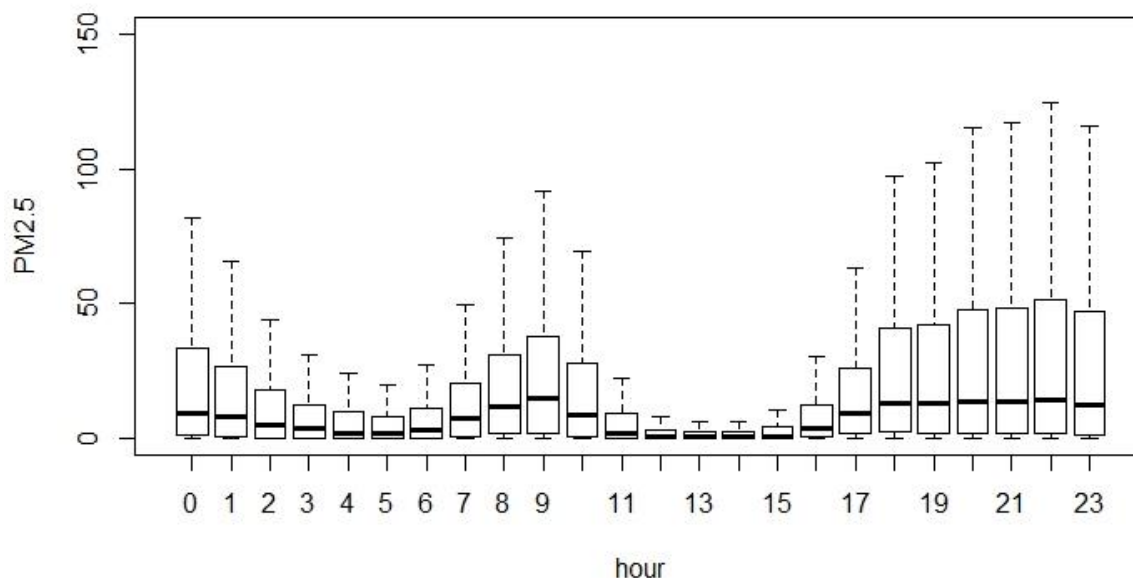
Figure 4-5: **Range of PM$_{2.5}$ concentrations across the whole ODIN network for each hour during phase 2 only.**

As can be seen from Figure 4-5, over the course of phase 2, on average, concentrations rose to a peak between 8 and 9am and covered a similar range to those between 5 and 6 pm. However, after this morning peak the concentrations would then fall, whereas in the evening high concentrations would persist or slightly increase further for the next 6 hours. The consequence was that concentrations **averaged over the whole of phase 2** in the morning were typically 50 – 60 % of the concentrations averaged over the whole night-time period. In phase 4 the difference had fallen to 36 % on average. On average, afternoon concentrations were a tenth of night-time concentrations. The very low concentrations every afternoon means that air quality effectively 'resets' every day.

4.2 Spatial variation in air quality

4.2.1 Technical note – method for producing maps of air quality

If data were available from every ODIN for all periods, maps summarising air quality could be easily produced by averaging up the data over whatever period is of interest. However, this is not easily done with the 2019 dataset due to different numbers of ODINs being deployed during different phases and data losses as described in sections 2 and 3 above.

To compensate for this, different techniques have been used to produce summary maps of the data captured.

The main technique used is to compare concentrations measured at each ODIN with those measured at one chosen as a reference unit. For this report ODIN #179 has been chosen as the reference. This is because it was deployed through all four phases at a site which is relatively central in the town

(Thames Street). It had one of the highest rates of data recovery and consistently recorded high concentrations relative to other sites.

In Figure 4-6 and Figure 4-7 below, concentrations for other sites are presented as the ratio of that site to the reference site, i.e. a value of 0 denotes clean air, a value of 0 – 1 is below the reference site, and a value above 1 is more polluted than the reference site. This technique allows data from different phases and different days to be combined without introducing bias. It is valid only if the spatial pattern is relatively stable and consistent between periods. Our analysis has confirmed this to be true at least for phases 1, 2 and 3. During phase 4 a slightly modified spatial pattern was observed (discussed further below).

4.2.2 Air quality patterns on winter nights

Figure 4-6 shows the pattern in average air quality during the night-time (4pm to 5am) for all nights in phases 2 and 3 (3rd July – 10th September). It only shows data from sites with more than 50 % data recovery each night to reduce bias. Phase 1 (June) has not been included due to significant data gaps. Phase 4 (late September and October) has not been included due to it exhibiting a slightly different spatial pattern.
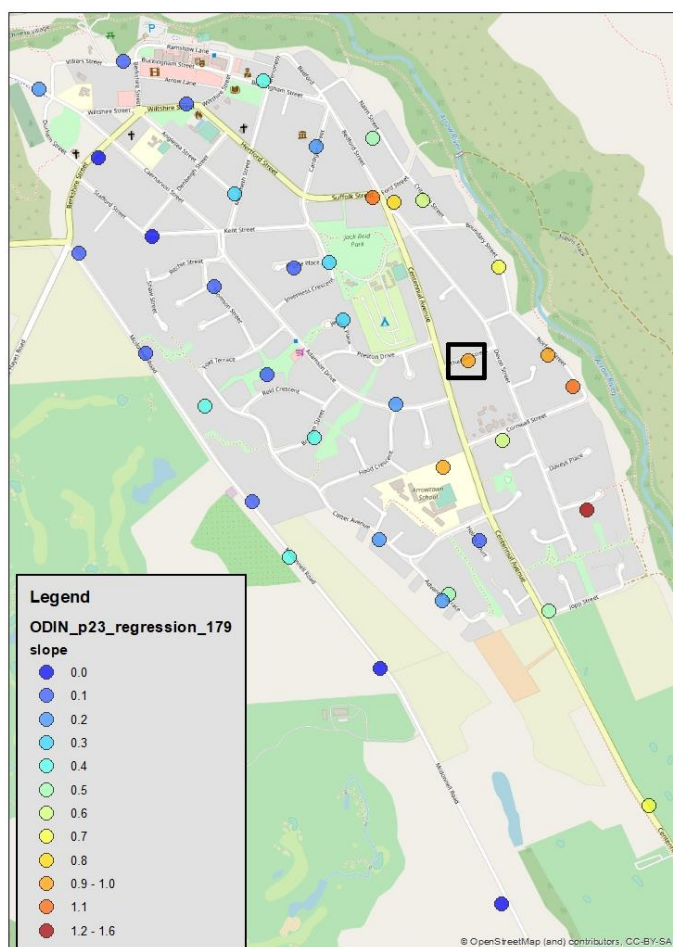
Figure 4-6:   Ratio of average night-time PM$_{2.5}$ concentrations at each site relative to the reference site (black box). Data for phases 2 and 3 only (3rd July - 10th September).

Figure 4-7 shows an interpolation of these data using kriging. The validity of this approach is yet to be confirmed through further research and as such this image should be considered indicative rather than definitive. In particular, the extent of the red and orange 'high concentration' zones may be an over- or under-estimate.
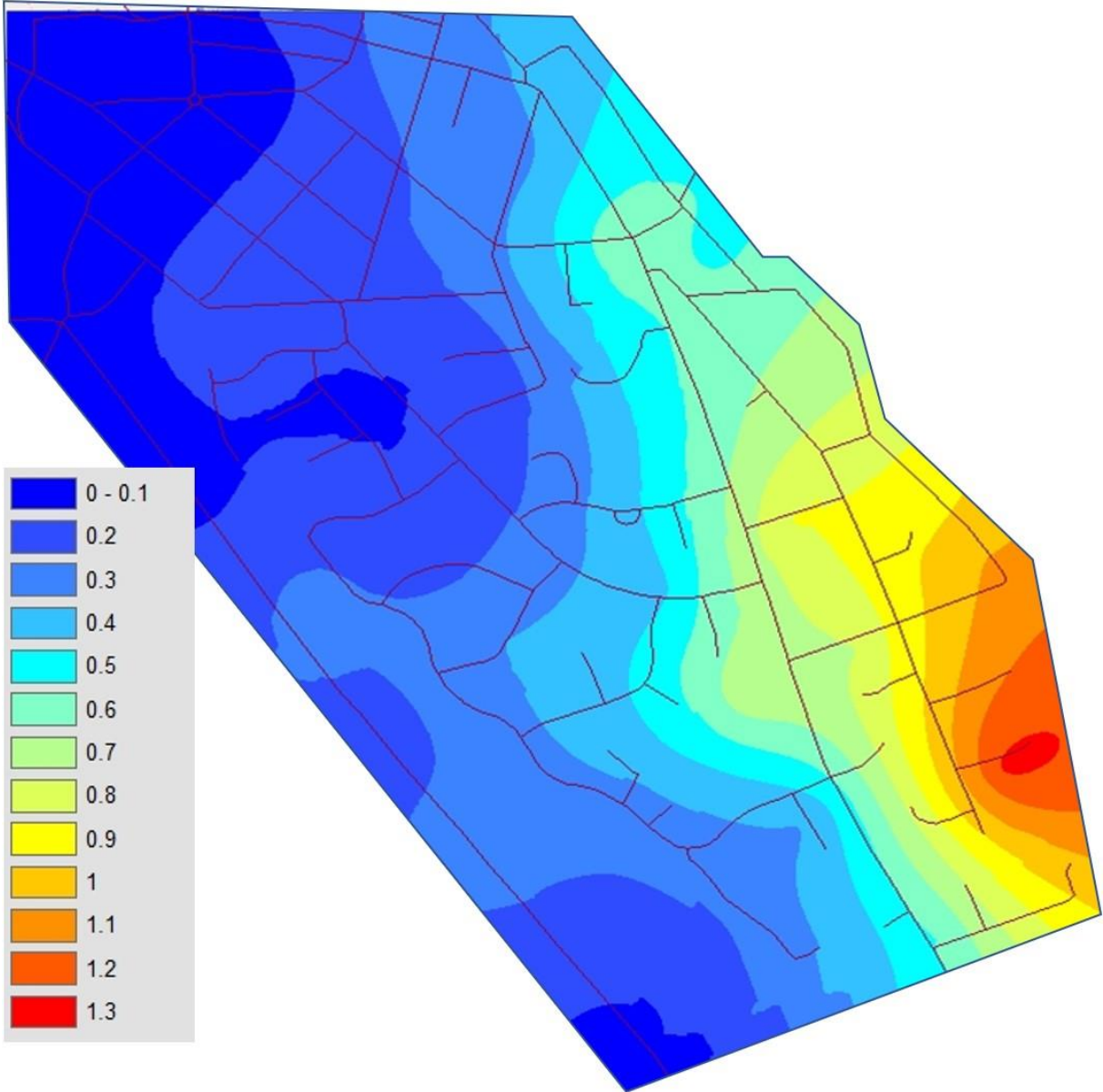

Figure 4-7:   **Estimated interpolated surface of the ratio of average night-time PM$_{2.5}$ concentrations at each site relative to the reference site.**

Figure 4-6 and Figure 4-7 show a very strong spatial gradient. Concentrations to the west of Centennial Avenue and Bedford Street ranged from 0 - 40 % of those at the reference site. To the east concentrations ranged from 40 – 105 % relative to the reference site.

There are three exceptions to this general pattern:

- The ODIN at the Arrowtown School car park recorded average concentrations 95 % relative to the reference site.

- The ODIN on Alexander Place recorded average concentrations 158 % relative to the reference site.

- The ODIN on the corner of Bedford Street and Suffolk Street recorded average concentrations 77 % relative to the reference site, which is higher than would be expected based on neighbouring ODINs.

Analysis to date has indicated that these anomalies are more likely due to localised high emissions, but instrumental error cannot yet be ruled out.

4.2.3 Air quality patterns on winter mornings

During phase 2, morning-average concentrations exhibited a spatial pattern with the same main features as during the night-time – principally a north-west to south-east gradient. However, there is some evidence that the shape of the pattern is slightly modified with relatively higher concentrations in the north and centre of the town and lower around the southern edges. On average, morning concentrations were approximately half of those in the night-time.

During phases 3 and 4, morning concentrations were generally low and relatively poorly correlated between ODINs. This suggests that either emissions had significantly reduced by this time (phase 3 began in mid-August), or that more increased winds or air turbulence (not measured during this study) associated with an earlier sunrise and warmer temperatures had increased dispersion, or (more likely), a combination of both.

4.2.4 Persistence/repeatability of patterns

Only a limited number of sites were monitored successfully during all four phases preventing a detailed analysis of the changes in spatial patterns across the course of the winter. However, initial analysis indicates that:

- Broadly, the average spatial pattern in concentrations was the same during each phase with a clear NW-SE gradient.

- There is some indication that there was a subtle shift in the spatial gradient during the campaign with long-term average concentrations falling faster at peripheral sites as the home heating season came to an end, relative to within the town's core.

5 Discussion and outstanding research issues

5.1 Gross emitters

A "gross emitter" is a term used to describe an emission source (in this case a wood-burning heater) that creates much higher emissions than is normal. Gross emitters can make a disproportionately large contribution to a local air quality problem. In principle, an appliance can be a temporary gross emitter (e.g. wet wood is occasionally used, instead of the normal dry wood), or a persistent gross emitter (due to poor maintenance, persistent misuse, persistent use of wet or otherwise inappropriate fuel, etc). Identifying gross emitters is of great value for regulators as mitigation of a single fireplace might make a large difference to local air quality, and especially the nuisance and risk posed to immediate neighbours.

In principle, gross emitters will create an anomalous local hotspot of poor air quality. With a dense enough ODIN network these localised hotspots may be detectable.

Throughout phases 1 to 3 of this study it was apparent that concentrations reported by ODIN #53, located on Alexander Place, were significantly higher than all other ODINs. An instrument error was suspected. Subsequently, this ODIN was duplicated in phase 4, when ODIN #209 was placed immediately above it. Unfortunately, ODIN #53 failed after 8 days. However, this was sufficient to show that the new ODIN recorded the same concentrations as the original, ruling out instrument error. This leaves the possibility of a genuine air quality hot spot in that area. Whether this means one or more gross emitters lie nearby is currently unknown. However, this area has now been identified as worthy of further investigation.

Research is ongoing to further develop a method for routine gross emitter detection.

5.2 Processes determining temporal variation – can we predict when poor air quality will occur?

High night-time concentrations were broadly associated with low air temperatures or rapidly falling temperatures in the late afternoon – consistent with rapid heat loss under clear skies and the formation of nocturnal inversions. High morning concentrations are currently being investigated.

However, analysis has yet to identify a set of predictor variables that can reliably predict high concentrations, indicating that either a complex combination of variables is required, or that the necessary data is either unavailable, or has yet to be included in the analysis. Ongoing research is investigating external sources of observed and virtual meteorological data.

Afternoon concentrations were very low. This indicates that polluted air is not accumulated in Arrowtown but replaced, with air quality effectively 'reset' every day.

5.3 Processes determining spatial variation – why is there a pollution gradient?

In principle there are two types of possible explanations for the high concentrations in the south-east of the town and low in the north-west: higher density of emissions towards the south-east, or transport of polluted air to the south-east where it accumulates, or both.

The observational study is not able, on its own, to give a definite explanation. Two pieces of evidence suggest differences in emissions may play a role:

- The 2013 census indicates a somewhat lower density of homes using wood as the principle source of home heating in the north of the town, with a higher density in the centre and south-east.

- Visible checks by ORC staff have indicated slightly higher frequency of observations of visibly smoking chimneys east of Centennial Ave, and in the town's centre (ORC, *personal comms.*).

- One ODIN in the south-east recorded anomalously high concentrations which may indicate one or more gross emitters nearby. This aspect will be researched further and reported elsewhere.

However, the limited analysis to date has identified several clues that also indicate a significant role for the transport and accumulation of polluted air:

- In the early evening concentrations stop rising, peak and begin falling earlier in the west (on the ridge) than in the east (in the valley). Some ODINs – mainly situated towards the Arrow River valley or along McDonnel Road - observed 'double peaks', consistent with the arrival of transported smoke after locally-generated smoke levels had peaked.

- The NW-SE gradient appears to be somewhat reduced in the morning relative to the night-time.

- The difference in PM$_{2.5}$ concentrations between the north-west of the town and the south-east is much greater than the difference in the proportion of homes who responded as using wood-burning for home heating in the Census.

These latter three observations are consistent with smoke being emitted relatively evenly across the town (except maybe in the north-west), but that smoke is then slowly transported on light winds that generally follow the terrain downhill. Although not directly observed in this study, it is well established in hilly terrain that when winds are light, air will slowly sink downhill in what are known as 'drainage flows'. These flows are strongest shortly after sunset and then weaken during the night. It is likely that drainage flows will regularly flow along the Arrow River valley from the NW towards the SE at night. This might be added to by weak flows off the ridge along the west of Arrowtown (Figure 5-1). In principle this would have the effect of transporting smoke emitted in the western side of town towards the eastern side of town where it will join the general flow along the river valley. In this way, the south-east corner of the town may well be exposed to smoke emissions from most or all the operating chimneys in the town. By the morning the drainage flows are weaker and – once the sun has risen – vertical mixing becomes more effective meaning there is less opportunity for smoke to flow and accumulate towards the south-east.
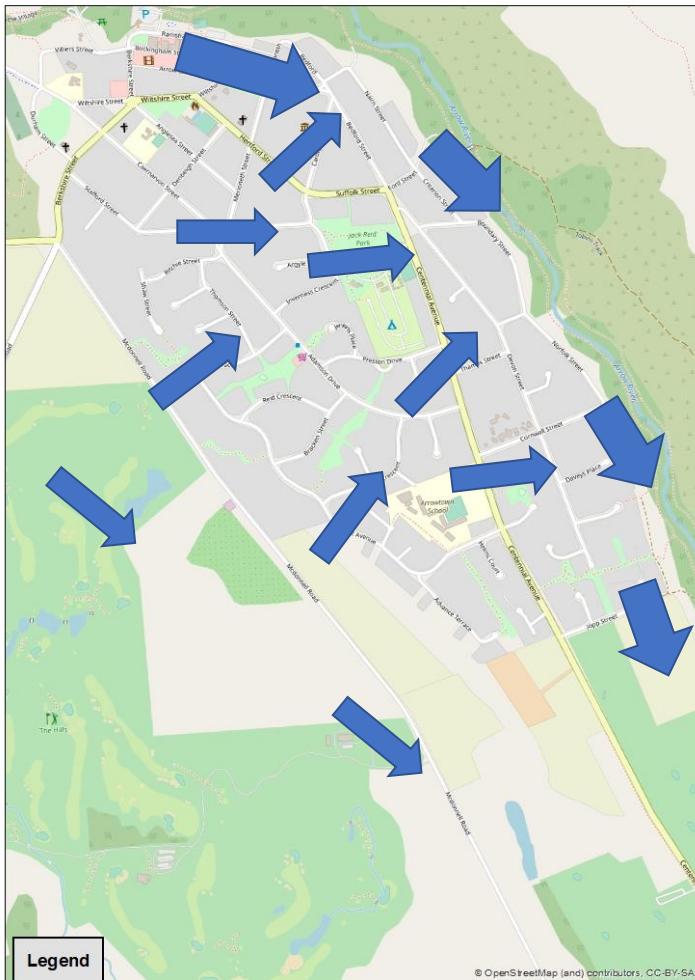
Figure 5-1: **Sketch of how possible terrain-following "drainage" air flows across Arrowtown on high pollution nights could transport smoke towards the south-east of Arrowtown.** These air flows are based on expert opinion and have not been verified by observation.

5.4 Agricultural and other emission sources

Agricultural smoke is more likely to be emitted in the daylight hours and particularly in the afternoon. Our initial analysis has not led us to suspect that agricultural sources have had a significant impact on our measurements. Future analyses will particularly focus on this issue.

A small network of ODINs was left behind at the end of phase 4 and has been operating continuously through summer 2019/20. The data generated during this period may be better suited to investigating non-heating emission sources. To date, it is notable that the network detected the impact of Australian bushfire smoke on 1st January 2020.

5.5 Summary of ongoing and future research needs

- Exploring whether the ODIN network can be used to detect temporary or persistent gross emitting chimneys.

- Exploring the degree to which temporal and spatial patterns in air quality can be predicted based on weather conditions, including exploration of existing meteorological data, or the need for new meteorological observations.

- Observational validation of the importance of drainage flows and the degree to which smoke is transported across the town, relative to spatial variations in emission density and strength.

- Developing methods to investigate the impact of agricultural burning as a contributing factor to air quality in Arrowtown.

6 Implications for stakeholders

6.1 The official (ORC) monitoring record and its interpretation

Regulation 15 of the Resource Management Regulations 2004 state that Regional Councils must conduct air quality monitoring if the Air Quality National Environmental Standard (NES) is breached in "that part of the airshed where… the standard is breached by the greatest margin or the standard is breached most frequently."

This study has confirmed that the permanent ORC air quality monitoring site meets that regulation in that it is located in the south-east of Arrowtown where PM concentrations are highest in mid-winter. However, our results also show that data from this site substantially over-represents concentrations found in the rest of the town. This is relevant when data from the site is used to represent population exposure, as (for instance) in health risk assessments such as found in the Ministry for the Environment's environmental reporting. A full winter's monitoring with a full ODIN grid will be able to quantify the degree of over-representation.

6.2 Risk of exceeding the current and proposed National Environmental Standards for Air Quality

At the time of writing there is a National Environmental Standard (NES) based on PM_{10}, of 50 $\mu g\ m^{-3}$ as a 24-hour average. The current Air Quality Regulations require that if any location within the airshed exceeds the NES, then the whole airshed is declared to have exceeded. As noted above, in terms of these Regulations, Arrowtown exceeded the PM_{10} standard 20 times in winter 2019, 7 times in July, based on regulatory monitoring at the ORC site.

Using the ODIN data from July, Figure 6-1 shows the number of days on which PM_{10} concentrations measured by the ODINs exceeded the current Standard. This value is zero everywhere, except at 4 sites in the south-east (including the reference site) where three values range from 6 – 8 days (i.e. similar to the official ORC record), and a fourth (Alexander Place) had 14 exceedances.

At the time of writing there is a proposal that a new National Environmental Standard will be introduced, based on $PM_{2.5}$, of 25 $\mu g\ m^{-3}$ as a 24-hour average. Figure 6-2 shows the number of days on which $PM_{2.5}$ concentrations exceeded this proposed National Environmental Standard during the month of July. Values range from zero at only two sites in the north-west corner of the town, to 21 times at the reference site and a peak of 25.

From our data we can conclude that if the $PM_{2.5}$ NES is adopted, then the number of days for which Arrowtown does not comply with the standard during mid-winter will increase from approximately 1-in-4 to 3-in-4.

Although not pertinent to the execution of the Regulations, our data also shows that the proportion of the town where air quality will exceed the NES will increase from perhaps one-quarter or less (the south-east corner) to nearly the whole town.
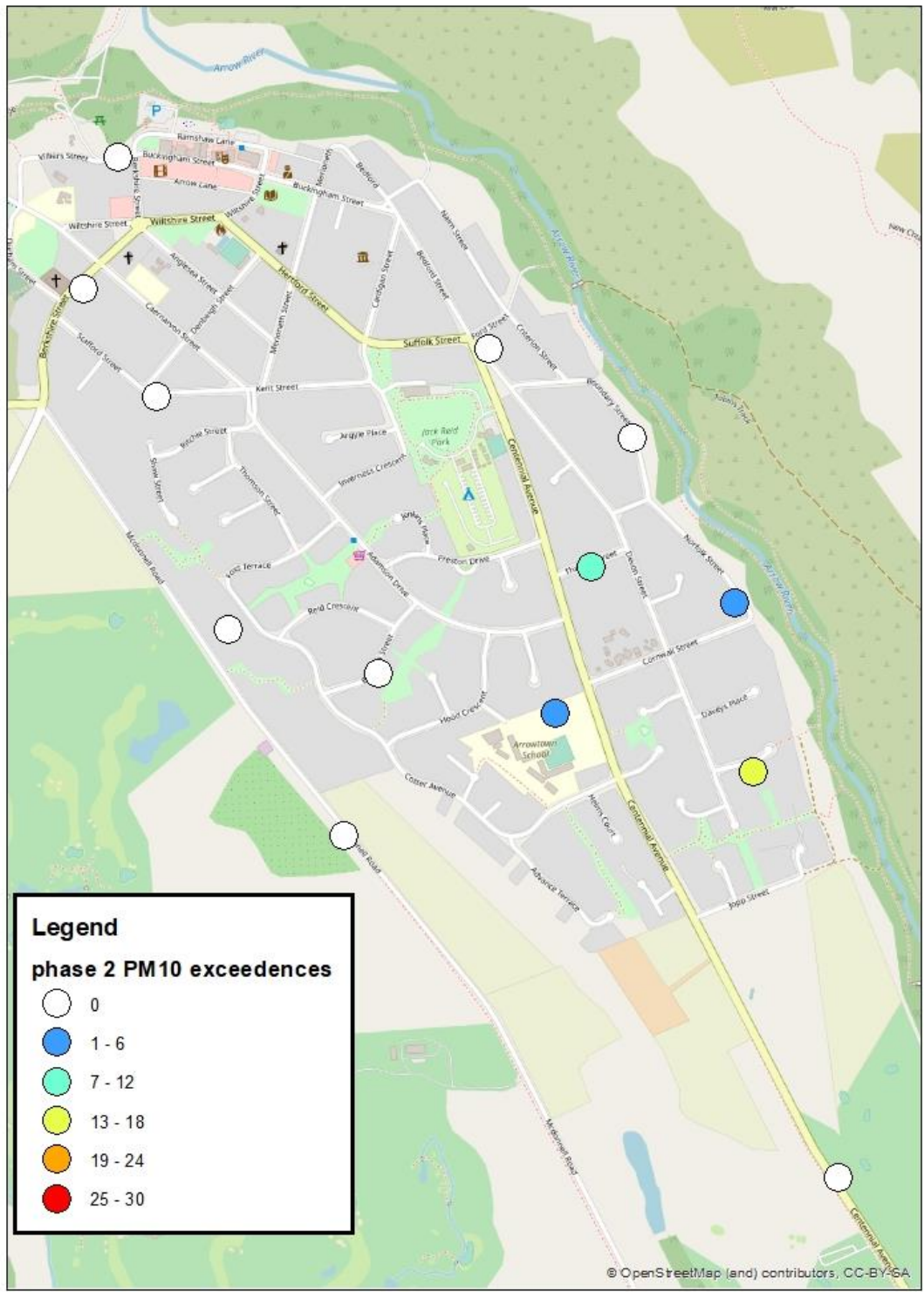
Figure 6-1: **Number of exceedances of the current National Environmental Standard for PM$_{10}$ during July.**
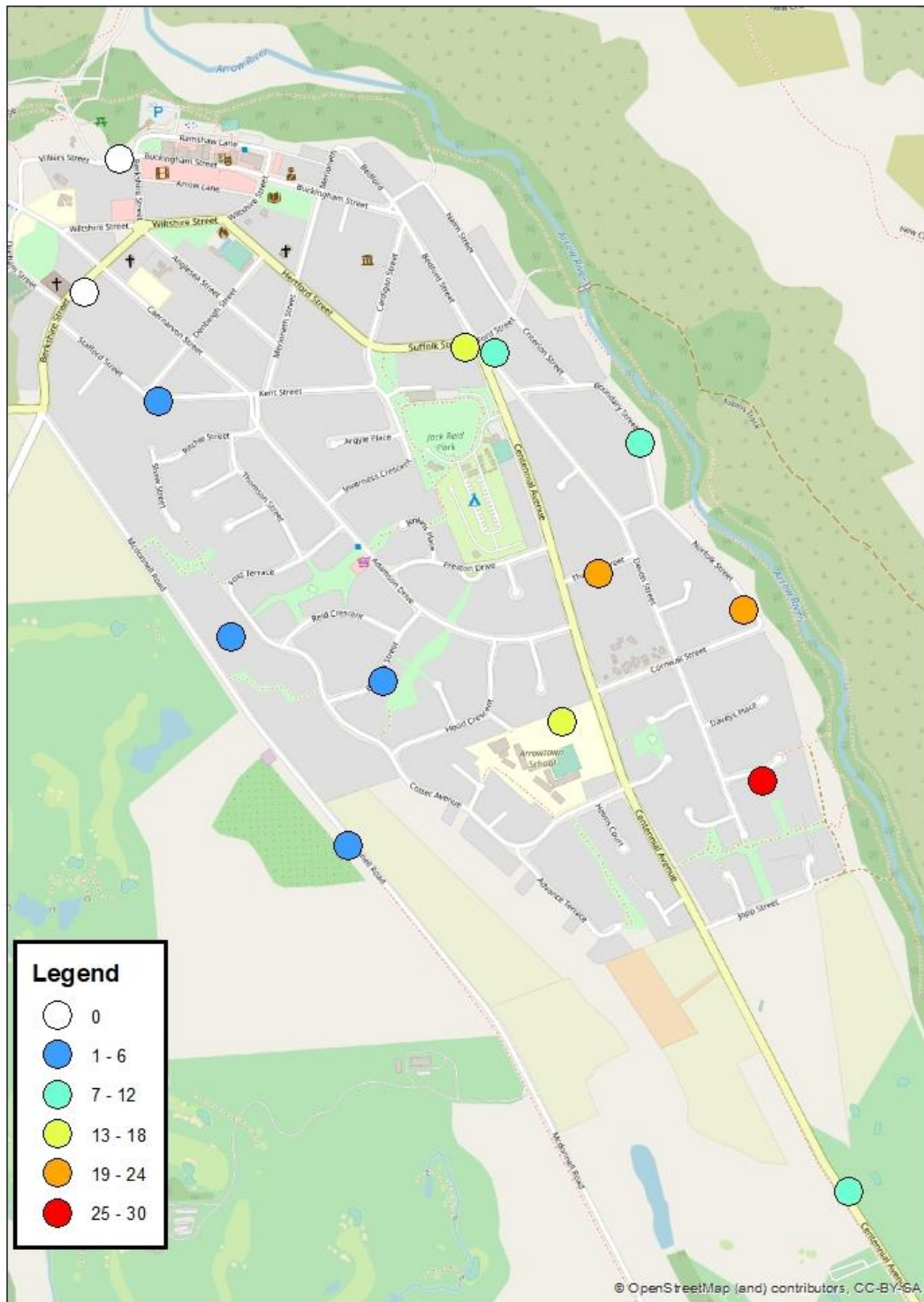
Figure 6-2: **Number of exceedances of the proposed National Environmental Standard for PM$_{2.5}$ during July.**

6.3 The public health risk posed by poor ambient air quality in Arrowtown

Our data has shown that, whilst every residence in the main part of Arrowtown is exposed to polluted air in winter, the degree varies hugely, with the highest risk in the south-east quadrant of the town (approximately east of Centennial Ave and south of Boundary Street). Whereas air quality

in this quadrant is likely to breech the current National Environmental Standard for air quality (PM_{10}), all the town (except the far north-west corner) is likely to breech the anticipated future Standard for $PM_{2.5}$.

However, the Standards do not imply a threshold for public health risk, but merely offer a set level of protection. Rather, the health risk is believed to be effectively proportional to the long-term exposure. Our data shows that this long-term exposure is approximately four times greater in the south-east than in the north-west of Arrowtown.

6.4   Concentrated versus dispersed intervention

Given the limited resources available to spend on reducing emissions, and the discovery of a localised hot-spot of poor air quality in Arrowtown, it is pertinent to consider whether it is better to attempt to focus efforts on reducing emissions over the town as a whole, or to concentrate efforts where they will have the most benefit. According to the 2013 census, the area we have identified as possessing the poorest air quality (east of Centennial Ave, south of Boundary Lane) contains around 165 homes which reported using wood as the primary source of home heating. A further 345 homes using wood heating lie outside of that area (a total of 510).

The data from this observational study alone is insufficient to quantify the likely outcome of different interventions. However, in principle there will be a trade-off. A more targeted intervention focussed on the 165 homes, or a subset of them, would most likely have a large impact over a small area (the hot-spot) – reducing the peak concentrations and reducing risk inequality across the town. Meanwhile a more evenly distributed intervention (aiming at all 510 homes) will tend to have a smaller impact over a larger area – reducing total exposure (and implied health burden) across the town because more people and homes are downwind of the intervention.

The data collected in this study can be used in a modelling study to attempt to quantify these effects. However, any predictions will remain uncertain. Greater certainty can be gained experimentally by conducting a spatially concentrated intervention within a CONA-style monitoring network.

7   Summary of conclusions

The following conclusions have a high certainty.

- Although the official (ORC) record shows that on cold winter nights Arrowtown has some of the most polluted air in the country, exceeding National Environmental Standards multiple times per year, NIWA's network of distributed monitors has shown that air quality varies hugely across the town.

- Our data confirms that air quality during the early afternoon period is excellent at all locations.

- Persistent and predictable poor air quality is limited to cold winter nights, with a smaller, secondary impact on subsequent mornings.

- During these conditions, air quality remains generally remains good in the north-west of the town, gradually deteriorating towards the south-east. A "high risk" zone for air quality exists in an area approximately to the east of Centennial Ave and south of Boundary Street.

- Our findings to date are entirely consistent with smoke from home heating being the overwhelmingly dominant source of particulate matter in the air during winter in Arrowtown. A preliminary inspection of the data shows no evidence of a major contribution from agricultural burning, although this will be investigated further.

The following conclusions have a degree of uncertainty and will be the subject of ongoing research.

- The data captured suggests that the dominant (and maybe only) cause of the differences in air quality across the town is the gentle flow of smoke downhill and its collection in the Arrow River valley, probably driven by cold air sinking down the slopes of the adjacent hills. Alternative explanations – including higher emissions in the south-east of the town due to colder conditions, more, older, mis-used or poorly maintained wood-burners – cannot be ruled out but appear less significant.

- The monitoring technology and approach has the potential to be used to identify locations containing homes with persistently abnormally high emissions ("gross emitters") and quantify their impact. To date, one such areas has been identified, and this will be the subject of further analysis.

- Results imply that actions to reduce emissions that were concentrated in the south-east of the town would be relatively more effective in reducing pollution concentrations where they are worst, reducing risk inequality and the number of exceedances of the NES. However, achieving the same emission reduction spread evenly across the town may be a more efficient way of reducing total exposure, and hence health risk, across the whole town.

8   Acknowledgements

Regulatory monitoring data was provided by Otago Regional Council.

Permission to install ODINs on streetlights was provided by Queenstown-Lakes District Council.

Permission to install ODINs on power poles was provided by Aurora Energy.