The influence of katabatic winds on dispersion of PM10 in the Richmond Airshed

By

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1. Introduction

Richmond township is located in the foothills of the Richmond ranges and on the edge of the Waimea plains. The dispersion of smoke (from home heating and outdoor rural burning in the wider area) is complex due to the local topography and climatic conditions.

Over the winter of 2020, the Richmond airshed exceeded the National environmental standards for air quality (NESAQ) PM10 standard 3 times, a total of 4 times in winter 2019, and a total of 12 times in winter 2018. There were also a number of days when there were near-breaches. These incidences have occurred when weather conditions have been cool and calm and coincided on days when there have been a number of permitted outdoor rural fires in the wider area. In recent years, Council has received increasing numbers of complaints regarding large outdoor rural fires in relation to smoke nuisance, visual amenity effects and concerns regarding human health impacts.

Analysis of 2018 winter PM10 data demonstrated that the Richmond airshed often experienced a ‘double peak’ of PM10 overnight (see Envirolink Report 1905-TSDC149). The first peak coincides with lighting up of wood burners in the early evening (typically between 17:30 – 19:00). However, wind direction and speed suggests that the second peak (typically between 23:30 – 01:30) may be from a ‘fugitive’ source outside the airshed (such as outdoor rural burning smoke) being pushed towards Richmond under the influence of the phenomena known as “katabatic wind”.

Council staff would like to understand (a) the influence of wind in the dispersion of PM_{10} in the Richmond airshed; (b) if there are katabatic winds in the wider area which influence PM_{10} dispersion overnight in the airshed; and (c) the extent/source of the winds.

In this report, a combination of data analysis and meteorological and dispersion modelling is performed to help understand the role of meteorology and the geographic placement of fugitive emissions in affecting the air quality of Richmond.

The advice will be used as part of a wider air quality research work programme which will help inform and justify any future resource management decisions, education and behaviour change programmes associated with air quality in the Tasman District.

2. Sources of Data:

Two different sources of data were used for this report, these are:

a) Data provided by the Tasman District Council in an Excel file that contained 30-minute averages of meteorology (as monitored at the Richmond Race Course) and pollutant species such as PM_{10} and $PM_{2.5}$ (as monitored at the Richmond Central at Plunket).The period of this dataset spans *1 January 2017 till 31 December 2020*.

b) *Simulated* data generated by The Air Pollution Model (TAPM) – which is a prognostic model that simulates meteorology and air pollution dispersion, in this case, for a few long-term selected episodes as outlined below in Section 3, Table 1. Episodes from two different years (2018 and 2020) were chosen instead of simulating each single exceedance event on its own. This approach not only simulates (samples) the days when PM was exceeded, but also samples other meteorological/dispersion events which allows for a statistically more robust way of examining the average meteorological/dispersion characteristics of the Richmond airshed.

3. The Air Pollution Model (TAPM):

TAPM version 4 was used to simulate ground level concentration of Particulate Matter (PM) for Richmond and the environs. TAPM is a three-dimensional incompressible, non-hydrostatic, primitive equations model, which uses a terrain-following coordinate system (Hurley, 2002) – *this essentially means that the TAPM is suitable for simulating meteorological and atmospheric dispersion characteristics of the complex mountainous landscapes of New Zealand*. The meteorological component of the model is supplied with a dataset derived from the Limited Area Prediction System (LAPS) analysis data from the Australian Bureau of Meteorology while the sea surface temperature is derived from Rand's global long term means at a resolution of 100 kilometres, although the prescribed values can be changed. The simulations presented here use four nested grids with a grid spacing of 30, 10, 3 and 1 kilometres, respectively. The meteorological model grid is configured with 50 zonal and meridional grid nodes; the pollution model of TAPM is designed with the same configuration. Default model options – such as soil temperature – were used since local information is scarce. *The quality of the dataset used to derive the TAPM dispersion model has been checked for New Zealand airsheds in previous research (Zawar-Reza et al. 2005) and is equal to the regionally modelled dispersion datasets produced by Golder and Associates for Regional Councils, since they basically use similar computational methodology to produce the datasets*.

To predict PM, the air pollution module of TAPM was used in a tracer mode (with no chemistry), a total of 4 tracer types were deployed. Tracers were released in point source configuration (Figure 1). TAPM was run for two long-term winter periods as specified in Table.

Table 1: Model Setup.

Meteorological Model Setup				
Simulation period	03 July to 21 July 2018 (*this period covers exceedance days of 4,5,6,19 and 20 of July*) 01 May to 31 August 2020 (*this period covers an entire winter season, for sampling of meteorological conditions in another year when exceedances also occurred*)			
	Grid-1	Grid-2	Grid-3	Grid-4
Grid spacing(metres)	30000	10000	3000	1000
Grid points	50	50	50	50
Vertical levels	25	25	25	25

4. TAPM dispersion simulation set-up:

The primary objective of the TAPM simulations are to study the impact of point source emissions from farmers burning combustible material and hence possibly impacting the air quality of Richmond – as monitored by the Tasman District Council. The burnings (source emission of PM) are highly variable spatially and temporally. It is very impractical to simulate the dispersion from a particular burn event on a given day, as day to day, the location and number of the burns can vary. Therefore a set number of point sources were defined in the model domain in the Richmond area (Figure 1), geographically delineating point source configurations with each point source grouping emitting their own PM tracer. The grid containing the RED, BLUE and ORANGE point sources has each point source separated by 0.5 km in the north-south direction, and 1.5 km in the east-west direction, while the YELLOW grid is 1.0 km east-west and 1.5 km north-south. The contribution of point source groupings, such as the groupings in RED as opposed to contribution from the YELLOW grouping, can be determined for Richmond, allowing us to examine the contribution of burnings in distinct geographical setting to Richmond's PM loading. Two scenarios were setup with TAPM, the first set specifies that the emission of PM from all point sources spans 24 hours, and in the second set, emitted PM into the atmosphere is only allowed between 10:00 to 16:00. The emission rate of PM is set to 5 grams per second for all, this value was determined using authors previous knowledge of PM emission profile from Christchurch and is only approximate. To my knowledge, no published emission profile (either measured or modelled) is available for farmer's burning practices. This emission rate is released by the model at from the ground level, then using the meteorological module of TAPM, mixing (turbulent mixing, and advection) in the atmosphere occurs and ground level concentrations are subsequently calculated.

Figure 1 Configuration and placement of point sources; Tracer 1 (RED), Tracer 2 (Blue), Tracer 3 (Orange), and Tracer 4 (Yellow)

5. Meteorological and physical setting:

Richmond is situated in a southwest-northeast oriented (wide) valley in a coastal environment (Figure 1). The meteorology of Richmond is typical of an area nestled in a complex mountainous landscape near the coast. The area experiences synoptically driven southeast flow bringing in cold air from the southerly fronts (Figure 2), but also has north-easterly winds that are a combination of synoptically driven air currents and/or thermally generated sea(land)-breeze local winds which result from coastal geography. These are evident in the wind rose plots (Figure 2), of particular interest for this report is the preponderance of nocturnal south-westerly katabatic flows, which have a potential to (re)circulate polluted air at night, when shallow inversion layers can trap PM near the ground exacerbating air quality.

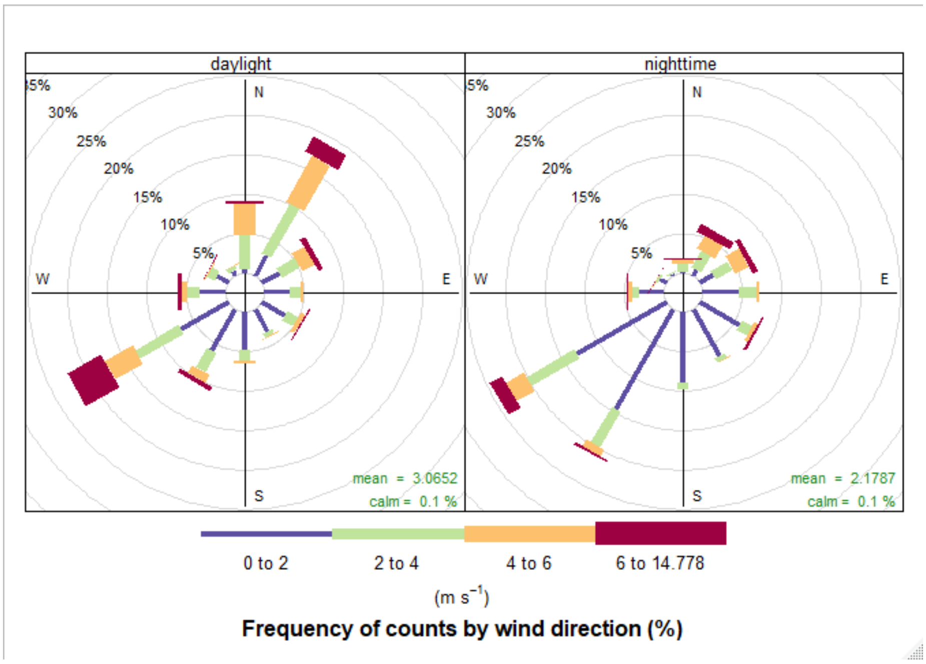

Figure 2 Wind Rose from the TDC data delineated into day and night time hours

Examination of the wind roses shows significant southwest-northeast channelling of air flow (Figure 2). Wind velocity in general tends to be higher during the day, but at night, there is a clear weakening. The night-time data shows a clear drop off in winds from the north-east sector, as there is a clear influence from the sea-breeze regime, and winds become more common from the south-west sector, given the low intensity of the wind and the fact that higher terrain dominates geographic perspective from this sector, these are most likely katabatic winds. Katabatic winds occur typically at night under clear sky conditions and are frequently less than 5 meters per second (m/s).

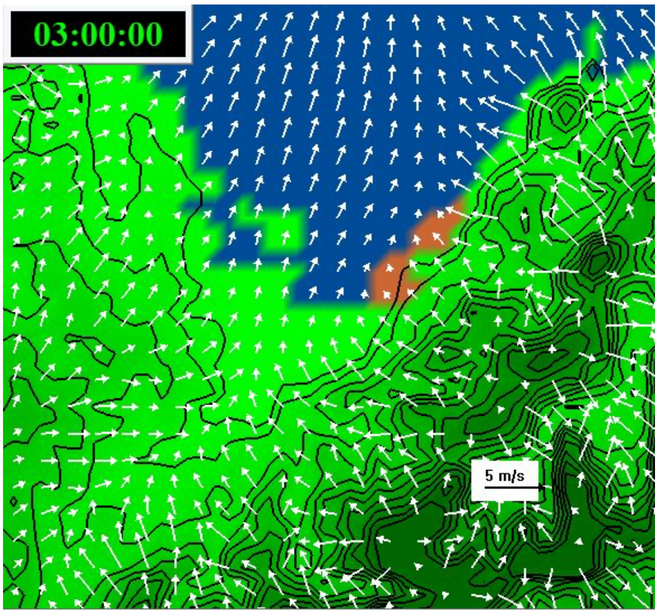

Figure 3 Modelled meteorological field - wind velocity at 10m above the ground for 21 July 2021 at mid-night. Contour lines indicate topography.

To further highlight the katabatic nature of the weak nocturnal south-westerly flow, TAPM also has a tendency of producing katabatic flows under settled anti-cyclonic synoptic conditions (Figure 3). The simulated wind vectors at 10 meters above the ground show a general tendency to drain towards lower elevation regions, the convergence of katabatic winds from elevated regions produces a generally southerly flow in the Richmond area.

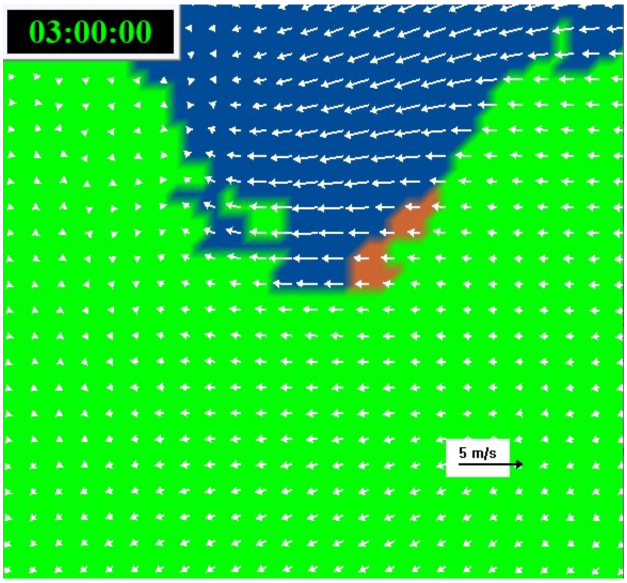

Figure 4 Modelled meteorological field for a set-up without topography - wind velocity at 10m above the ground at mid-night.

Since TAPM is a physics based model, we can use it in an unconventional way to show that the resultant wind field in Figure 3 have katabatic origins. This goes as follows, katabatic winds are simply cold air draining down the slope under the influence of gravity – since cold air is less buoyant than warm air. Therefore if topography (i.e. sloping terrain) is removed from the modelled domain, then katabatic winds should cease to exit. Figure 4 shows the result of such as experiment with TAPM, where the topography is removed from TAPM (everything location in the terrain is at sea level height). In this case, the only significant airflow at mid-night is a weak easterly over the water body, with calm winds over the ground.

6. Air Pollution Climatology:

The plots in this section of the report are produced in R by a Data Science package called Openair (https://davidcarslaw.github.io/openair/). Openair has been developed for analysing and providing visualization toolkit for air quality data. The code used to generate the plots in this report can be provided upon request.

The polar-annulus plots link wind speed and time of day to average PM10 and PM2.5 concentrations to highlight diurnal patterns in these variables for January 2017 till 31 December 2020 (Figure 5) and winter episodes to narrow the focus on winter meteorology/dispersion characteristics of the airshed (Figure 6). The diurnal nature of PM concentrations is evident (as rings around the plot). Yet typically the highest concentrations occur after 18:00 from the south-west quadrant – so nocturnal air flows, most likely with a katabatic signature.

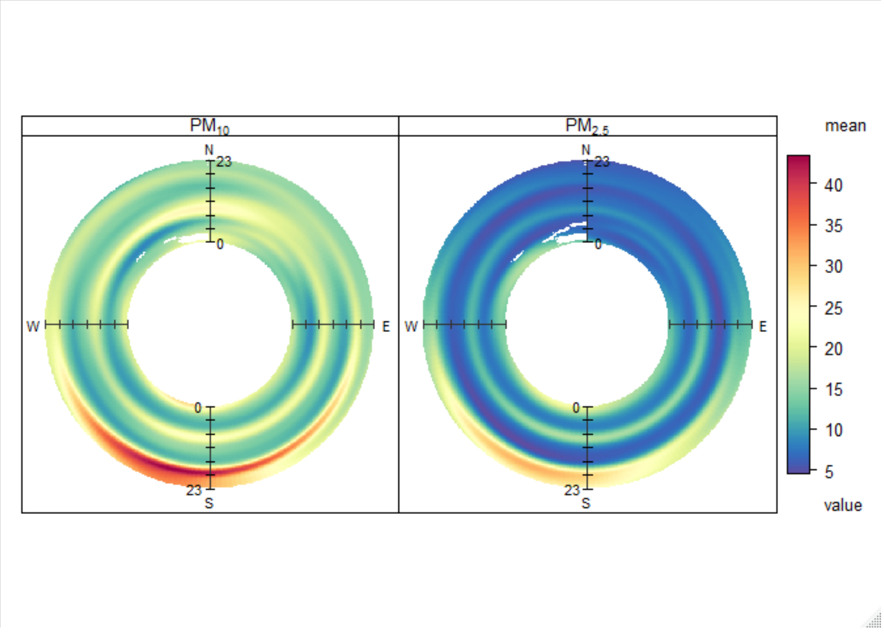

Figure 5 Polarannulus of PM Data for January 2017 till 31 December 2020 plotted with Richmond Racecourse meteorology

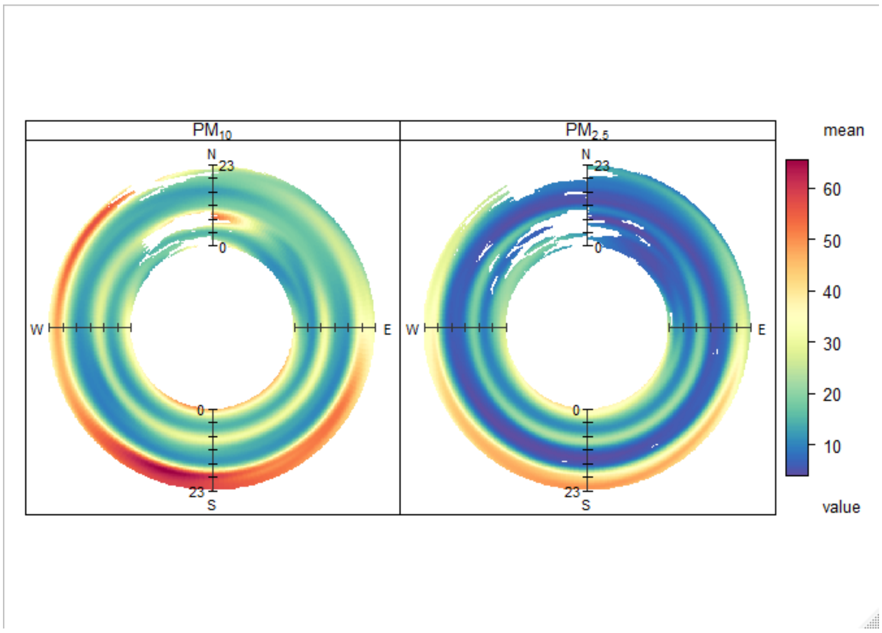

Figure 6 Polarannulus of winters only PM with Richmond Racecourse meteorology

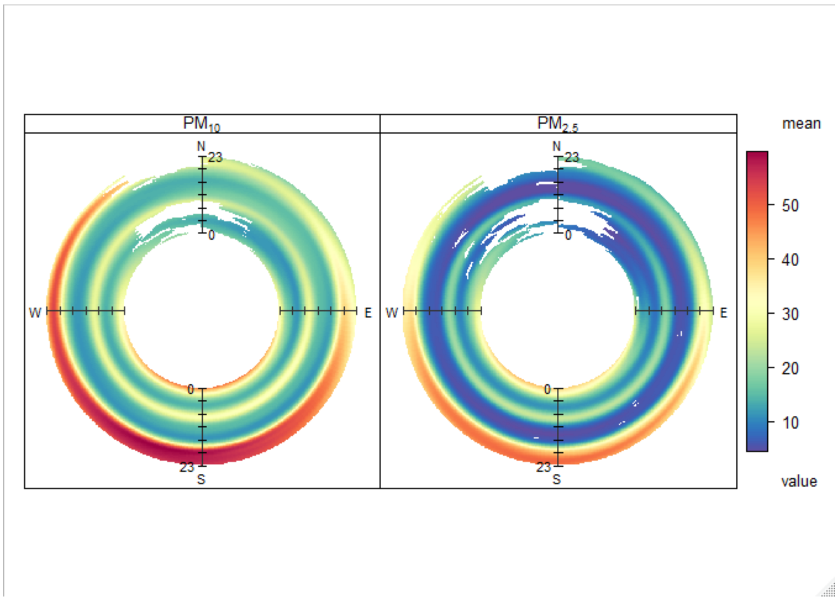

Figure 7 Same as previous figure except when wind speed is less than 5 m/s

To filter out the effect of synoptic scale storms that produce the cold south-westerly winds, winter polarannulus plots are reproduced, but for episodes when wind speed is less than 5 m/s (Figure 7). This is done since katabatic flows in this region will be in order of such intensities. Therefore it is evident that the nocturnal katabatic wind regime advects (transports horizontally) significant air from the south-west quadrant of the Richmond environment. If this air is polluted, then it impacts the air quality of Richmond.

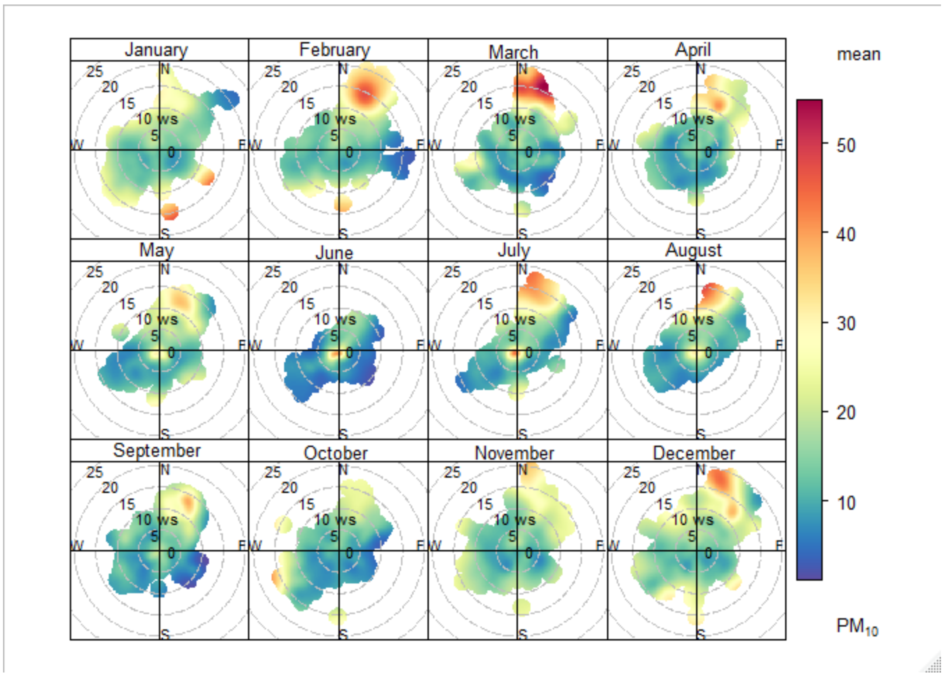

Figure 8 Polar Plot PM10 (µg/m^{-3}) for January 2017 till 31 December 2020 data for Richmond PM10 and Racecourse meteorology.

The Polar plots in Figures 8 and 9 are meant to show the climatology of PM_{10} and $PM_{2.5}$ source regions, respectively. The May, June, July, August months in both figures show that the highest concentrations when wind speed is below 5 m/s is skewed towards the south-west sector, this shows that influence of the katabatic winds in contributing to the PM loading of the air, which is the meteorological condition that this report has focused on. However, other interesting patters can also be discerned, such as the high concentrations from the north-east sector for high wind speeds (> 10 m/s) in February, March, and April (Figure 8, 9), which could be showing the influence of salt particles on PM_{10} concentration, and less so on $PM_{2.5}$.

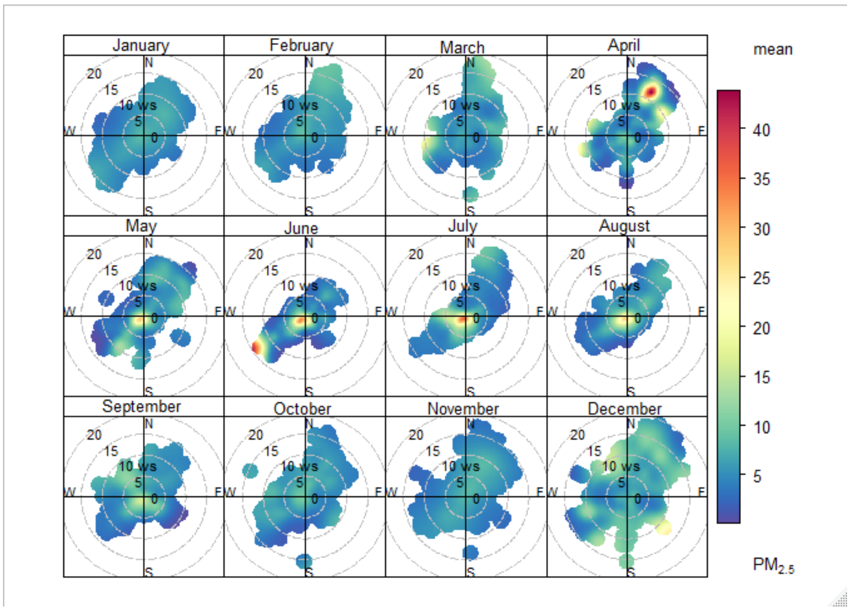

Figure 9 Polar Plot of PM2.5 (µg/m^{-3}) for January 2017 till 31 December 2020 data for Richmond PM10 and Racecourse meteorology

The trend level plots in Figures 10 and 11 show several useful ways of visualizing the data, but for the purpose this report, focus should be on the top time-series plot which hourly-averages and categorizes the measured PM data on a weekday basis, examining the data in this way helps in elucidating the patterns of human activity in the data. For example, the impact of transport/industry can be clearly discerned in the difference between the weekday weekend peaks in the morning. The $PM_{2.5}$ concentrations also show a third pre-night peak which might be the result of fugitive burnings.

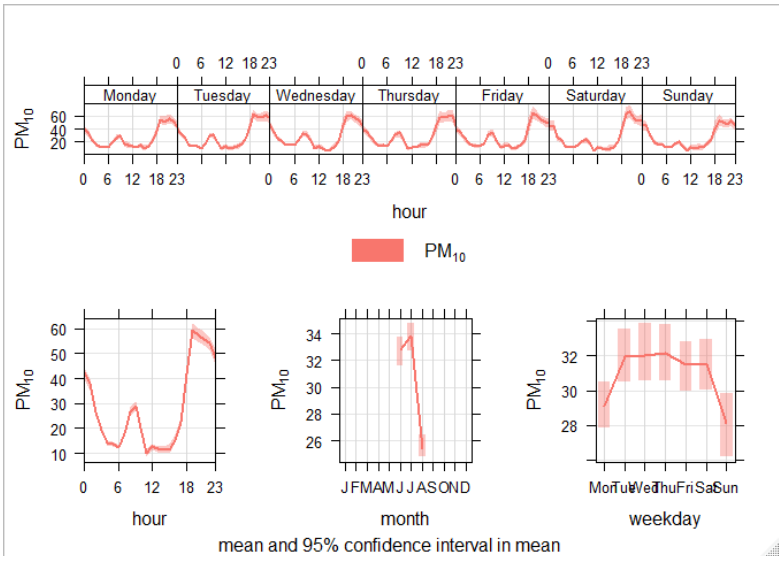

Figure 10 winter months, wind Speed less that 5m/s Wind Direction with any southerly component

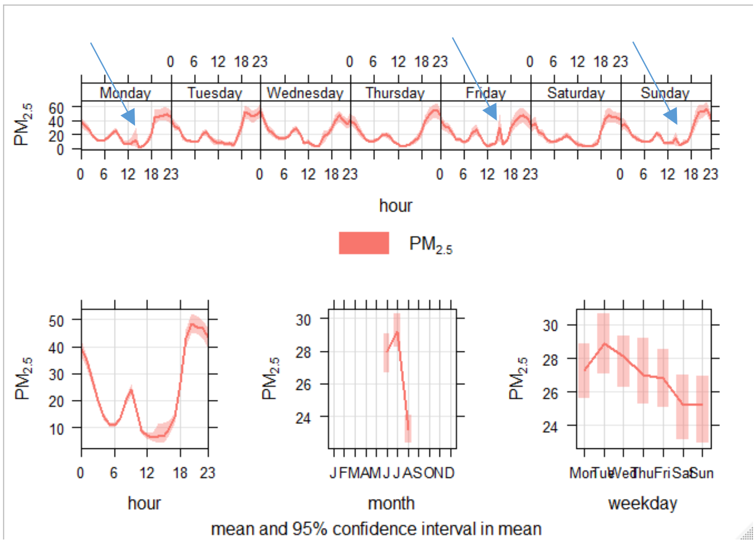

Figure 11 PM2.5 Winter months, wind speed less than 5m/s Wind Direction with any southerly component. The BLUE arrow points at the third pre-night peak.

7. TAPM dispersion results:

Air pollution concentrations near the ground are typically controlled by wind speed and the mixing depth of the atmosphere which can vary temporally and spatially. On average, wind speed and mixing depth tend to be higher during the day, so the ventilating capacity of the air tends to be at maximum leading to low pollution loading. At night, with the cooling of the ground, a surfaced-based inversion typically forms, which reduces wind speed, suppresses the mixing depth, thereby reducing the atmospheres ventilating capability, leading to higher air pollution concentrations. The TAPM simulated concentration of PM from modelling scenarios also shows that the contribution of PM to Richmond's PM concentration from the burn sources are lowest between 11:00 and 16:00 (Figures 10, and 11).

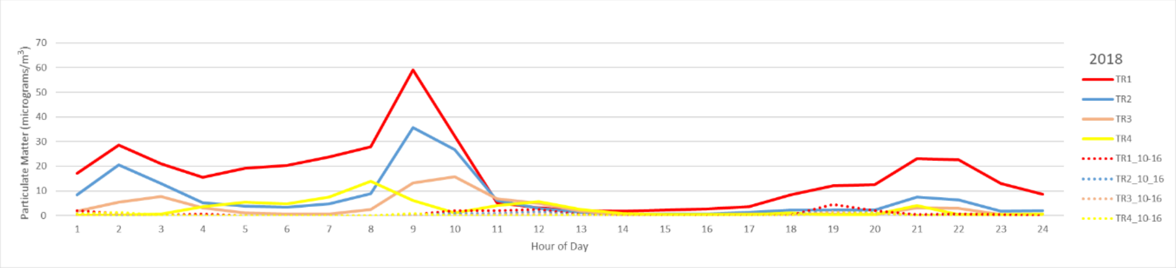

Figure 12 Hourly-Averaged simulated PM concentrations over Richmond for 2018 dispersion model runs. Colouring of tracers as in Figure 1, solid lines for 24-hour emission profile, dashed lines for emission of PM from 10:00 till 16:00.

The simulated PM concentration in Figures 11 and 12 are time-averaged for each hour of the day to elucidate the diurnal signature in the data. In general, all regions have the potential to contribute to elevated PM concentrations over the monitoring site, but this influence is greater before 11:00 and after 16:00, when the mixing depth is typically suppressed as the result of the surface-based inversion layer. The strength of contribution to PM concentrations decreases the further the source region from Richmond. When the emission from point sources is restricted to between 10:00 and 16:00, the PM contribution becomes negligible as the emission of PM is occurring into an atmosphere that has a greater mixing depth and higher wind speeds as the result of the sea and valley winds.

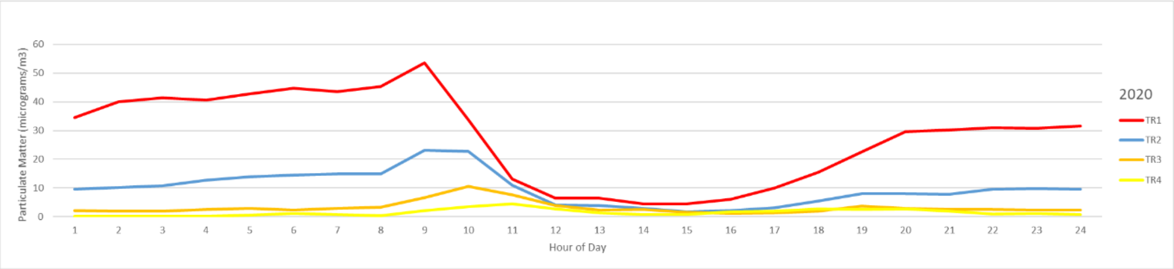

Figure 13 Hourly-Averaged simulated PM concentrations over Richmond for 2020 dispersion model runs. Colouring of tracers as in Figure 1. Only the 24-hour emission profile was performed for this year.

8. Conclusion:

The combination of data analysis and PM dispersion modelling with TAPM has shown that:

- Katabatic winds can occur after sunset and advect (horizontally transport) pollutants towards Richmond, the spatial nature of the katabatic flow has been shown by TAPM, but it is generally an extensive flow system.
- The point sources as simulated here have the potential to contribute to PM loading of the air over Richmond, this potential decreases the further the point source region from Richmond.
- Dispersion results shows that the best time to emit PM into the air is during the day time between 11:00 and 16:00, when it has the least impact on the Richmond airshed as a result of daytime winds and the greater ability of the atmosphere to disperse PM.

REFERENCES:

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Zawar-Reza, P., Kingham, S., & Pearce, J. (2005). Evaluation of a year-long dispersion modelling of PM10 using the mesoscale model TAPM for Christchurch, New Zealand. *Science of the Total Environment*, *349*(1-3), 249-259.