ESTIMATING TASMANIAN WINTER-TIME POPULATION EXPOSURE TO $PM_{2.5}$ USING A TWO-PARAMETER, EMPIRICALLY-BASED METHOD

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Abstract

From 2018 Australian jurisdictions are to report annual population exposure to $PM_{2.5}$ under the revised National Environmental Protection (Ambient Air Quality) Measure (the 'Air NEPM'). Discussion has occurred, and continues, among jurisdictions to determine nationally consistent approaches for this assessment and reporting.

In Tasmania a significant contribution to annual particle exposure is winter-time smoke from woodheaters/woodburners. This paper presents exploratory work using the data from the near-statewide air network and car-based smoke measurement surveys on $PM_{2.5}$ levels from towns and communities across Tasmania, to derive population exposure estimates.

Extensive smoke surveys in Launceston in winters 205 and 2017 indicated that the spatial distribution of mean winter $PM_{2.5}$ was correlated with the woodheater distribution. Spatially-resolved woodheater densities are not available for all of Tasmania, but for the stations where woodheater data are present it was found that the relationship between the station winter mean $PM_{2.5}$ and local woodheater numbers is approximately:

Winter-mean $PM_{2.5} \sim (N/20)\ \mu g/m^3$,

where N is the number of woodheaters in a 1 km radius from the station.

A parabolic expression between mean $PM_{2.5}$ and woodheater number, including an empirically derived wind-speed correction to account for variations between winters, provides a better description. This was applied to all 35 stations, for all winter-seasons where data exist, using woodheater numbers from survey data or derived from housing densities. From the total of 231 'station-winter' instances, the mean residual $PM_{2.5}$ (measured-predicted) was -0.5 $\mu g/m^3$, with a standard deviation of 3.7 $\mu g/m^3$. The approach may have applicability for areas of Tasmania with no air quality measurements, and hence could provide a method to estimate statewide population exposure.

The paper will describe this work, and also will explore the physical basis as to why the 'Winter-mean $PM_{2.5} \sim (N/20)\ \mu g/m^3$' relation may exist in Tasmania.

Keywords: *Population exposure, woodheater/woodburner smoke, naive speculation, $PM_{2.5}$.*

1. Introduction

1. Population Exposure to particles

The 2015 variation to Australia's National Environmental Protection (Ambient Air Quality) Measure (hereafter the 'Air NEPM') requires all Australian jurisdictions to report annually, from 2018, population exposure to particles as $PM_{2.5}$. Following this, many jurisdictions are considering appropriate methodologies to meet these requirements. The Air NEPM also notes that there should be national consistency in the reporting of these estimates. This paper presents some work conducted in Tasmania on the feasibility of deriving population exposure estimates using a semi-empirical approach.

2. Tasmanian circumstances

The relatively small population, temperate latitude, and few large-scale industrial facilities means that Air NEPM criteria pollutants of ozone, oxides of nitrogen and sulphur dioxide are mostly at very low ambient levels. However elevated $PM_{2.5}$ from biomass burning is a significant air quality issue across the state. Smoke sources include winter-time woodheaters, planned burning operations, and bushfires (wildfires). Recognising this, a distributed smoke monitoring network began to be established in Tasmania in 2009. This is the Base-Line Air Network of EPA Tasmania ('BLANkET'), and currently consists of 35 stations measuring indicative (but calibrated) PM_{10} and $PM_{2.5}$, spread across most of the state with the exception of the sparsely-populated south-west. A car-based instrument has also been used for smoke surveys to create maps of smoke distributions using geo-located $PM_{2.5}$ measurements from a moving vehicle.

2. A semi-empirical approach to winter-time $PM_{2.5}$ population exposure estimation

1. Basis of the method

An analysis of two winter-seasons of car-based smoke surveys in Launceston provided some evidence that there were consistent areas of elevated $PM_{2.5}$ which appeared to relate to the number of woodheaters in the area (Innis et al, 2017). Hence an investigation was conducted using the fixed-station data to assess whether mean winter $PM_{2.5}$ was also related to the number of woodheaters nearby each station. For the purposes of this study, and guided by the Launceston survey analysis, woodheater counts were estimated within a 1 km radius of a station.

2. Estimating woodheater numbers

In 2011 EPA Tasmania commissioned a telephone survey of woodheater use in Tasmania. [https://epa.tas.gov.au/epa/air/woodheater-smoke/woodheater-and-open-fire-census-2011]. The survey was not statewide but was focussed on twenty-six representative areas of the state, including Hobart and Launceston. A number of these 26 areas were selected as they were known or suspected of experiencing poor winter-time air quality. In fourteen of these areas BLANkET stations were either present or were installed in the years following the phone survey. The survey results were presented as percentages of home using woodheaters as the primary heating source. The type of heater was identified as either a closed heater or open fire. The number of open fires in active use was found to be very low, and these will not be considered further. Recent inspection of these data for the work reported here suggests there may have been a sampling biases towards more rural mesh blocks, but the results of the survey have been used without any further adjustment.

The Australia Bureau of Statistics (ABS) mesh-block data were used to estimate the number of dwelling within a 1 km radius of each BLANkET station. The mesh-block data were imported into the QGIS spatial analysis program and 1 km buffers were created around each station. (The data importation and buffer-creation work was carried out by EPA Tasmania officer E. Cox.) Figure 1 illustrates the method for Latrobe, north-central Tasmania. For mesh blocks that fell wholly within the buffer, the number of dwellings was directly available from QGIS-queries. A manual method was used for mesh blocks that were partly in the buffer – in these cases each mesh block, for each station, was inspected by eye, and the number of dwellings in these block that were inside the buffer were manually added to the query output.

For the fourteen-areas where the phone survey was carried out that surrounds a BLANkET station, the woodheater number in the 1 km buffer was derived simply by multiplying the percentage woodheater use by the number of dwellings. It is noted that the experimental uncertainties of this approach may be large due to the relatively sparse nature of the phone survey for any given area. It was also noted that the median percentage of dwellings using woodheaters in these areas was near 40%.

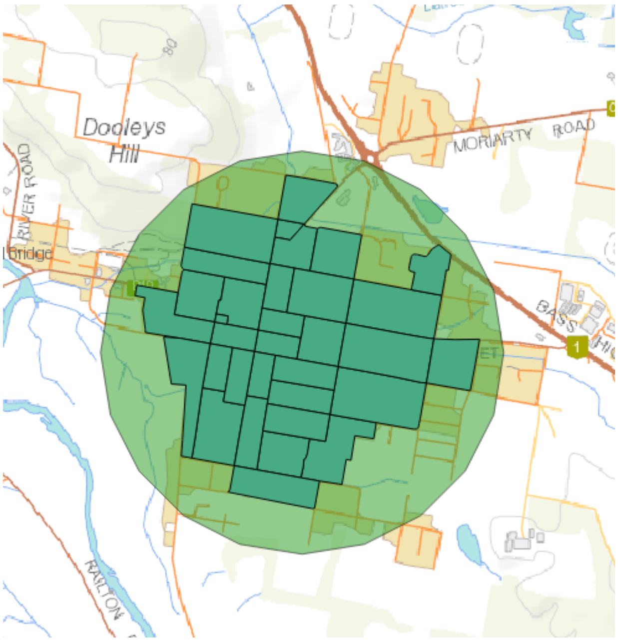

Illustration 1: Map showing a 1 km buffer around Latrobe air station, northern Tasmania, and ABS mesh blocks that are wholly within it.

3. Results

1. Mean winter $PM_{2.5}$ versus woodheater number

Figure 2 shows for these fourteen stations, for the winter of 2014, a plot of mean winter $PM_{2.5}$ versus derived woodheater number in a 1 km buffer. Plots for other years of data are similar. There is some correlation in that the stations with higher numbers of nearby woodheaters often have higher mean winter $PM_{2.5}$ levels.

From inspection of several winter seasons of such data-plots, it is seen, that approximately, the number of woodheaters in the 1 km buffer, divided by 20, gives a line that in some measure describes the mean relationship seen in the data. That is,

$$\langle PM_{2.5} \rangle \sim N / 20 \qquad (1)$$

where $\langle PM_{2.5} \rangle$ is the mean winter-time PM2.5, and N is the number of heaters within 1 km of the air station. The appendix explores a possible physical basis for this relationship.

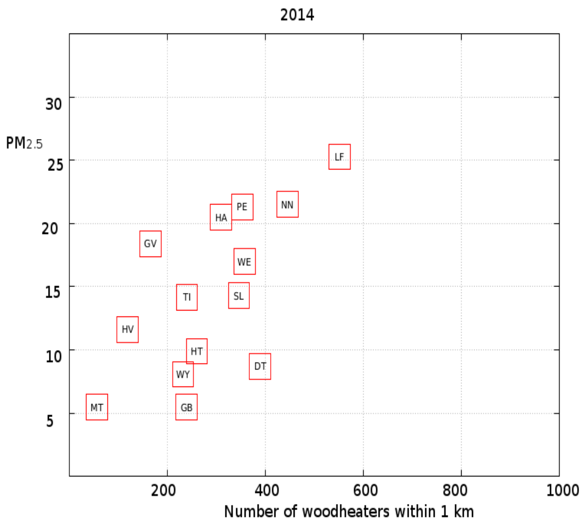

Illustration 2: Mean winter $PM_{2.5}$ (µg/m^3) versus estimated nearby woodheater numbers for the 14 stations where the home-heating phone survey was conducted.

2. Extending to stations in areas with unknown woodheater numbers.

For the 21 BLANkET stations in areas the telephone woodheater-use survey did not include, the median percentage woodheater-use of 40% was adopted. This is an unfounded assumption for any given area, and clearly needs to be investigated further. However in the absence of more detailed data it is adopted here, and can be considered very likely to be correct to within a factor of two. (i.e., the percentage of dwellings that use a woodheater near any of these stations is almost certainly in the range from 20% to 80%.)

3. Estimating winter-time $PM_{2.5}$ from woodheater numbers and wind-distributions

Combining all available winter-seasons for all BLANkET stations onto the one axis gives the plot shown in Figure 3. Some non-linearity is suggested. This is represented in an post-hoc approach by a parabolic (2^{nd} order polynomial) fit, which is shown by the blue symbols in the plot. This parabola can taken as an estimate of winter-mean $PM_{2.5}$ prior to applying a correction based on wind-speed distribution. The wind correction, discussed below, can in part account for differences in inter-annual meteorology.

In Tasmania, the woodheater smoke levels on any given night are greatly affected by the local wind speed: Even a light breeze significantly contributes to smoke dispersion. The winter $PM_{2.5}$ and meteorological data were inspected and a second, post-hoc relationship was derived, this time as a correction for varying inter-annual wind conditions. This considered the distribution of wind speeds during the night hours (when smoke is highest) over the winter, and reduced the mean winter $PM_{2.5}$ levels on a sliding scale for an increase in the fraction of hours of wind speeds over 0.25 m/s.

Due to the uncertainties in the experimental data (such as woodheater number) the exact formulation of these corrections are probably less important than the conceptual approach: In principle the parabolic fit to woodheater numbers and the wind correction yields a two—parameter estimation of mean winter $PM_{2.5}$ levels.

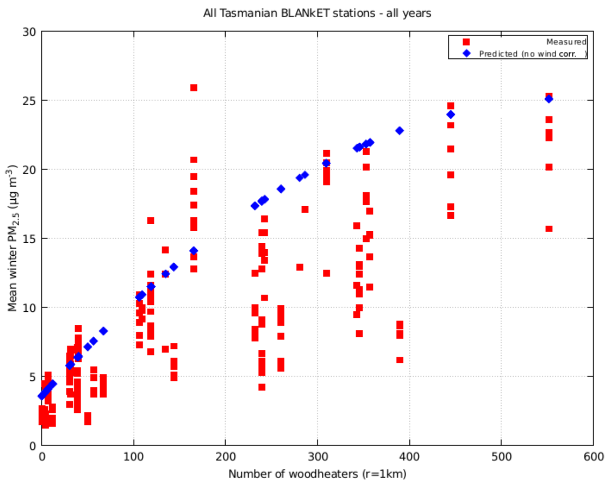

Illustration 3: All available winter-seasons data for mean winter $PM_{2.5}$ for all BLANkET stations and all available years versus estimated woodheater number. The blue symbols delineate a parabola as discussed in the text.

4. Applying the two-parameter estimation to individual years.

Figure 4 shows examples of applying the two-parameter estimation method for two individual stations for the available winter seasons. In the top panel data are shown for South Launceston. The measured (actual) mean winter $PM_{2.5}$ and two-parameter predicted winter $PM_{2.5}$ data are shown. The predicted values are above the measured values for all winter seasons, but the general trend in the predicted values often mimics the measured data. Woodheater-use data were available for the South Launceston area.

The lower panel of Figure 4 shows the measured and two-parameter predicted winter $PM_{2.5}$ for Deloraine station. There are no woodheater-use data for Deloraine, so the value of 40% noted earlier has been used here. There is a very good measure of agreement between the measured and predicted values, which must be considered to an extent to be fortuitous in absolute terms (being directly dependent on the assumed percentage of dwellings using woodheaters), but the close agreement for the inter-annual variation is of interest. It should be noted that the two-parameter fit was derived solely from data from the 14 stations where woodheater use information was available (and hence did not include Deloraine). The agreement shown for Deloraine between the actual and predicted values should at present be considered to be of interest, but it is not at all conclusive that the approach has any general validity. The agreement between predicted and measured $PM_{2.5}$ for the other Tasmanian stations varies from good agreement (as for Deloraine) to poorer agreement (such as for South Launceston).

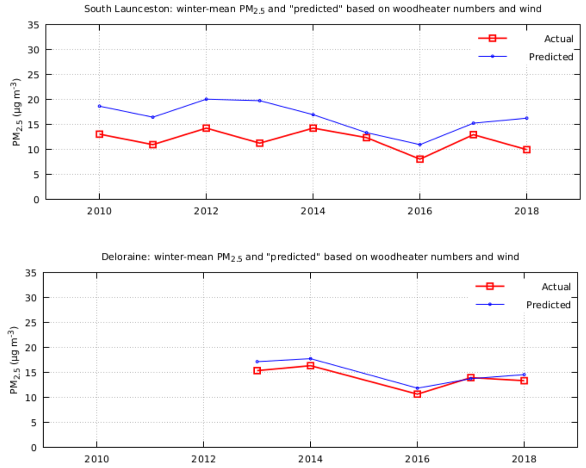

Illustration 4: Actual (open red squares) and two-parameter predicted (small blue symbols) mean winter $PM_{2.5}$ for South Launceston station (top panel) and Deloraine station (lower panel), for available years of data for the stations.

Applying the two-parameter fit to all BLANkET stations for all available years to estimated winter $PM_{2.5}$ gives the plot shown in Figure 5. This includes the 14 stations where woodheater information was available, and the 21 stations where woodheater use was assumed to be 40% of residences within the 1 km radius of the station.

There is a general level of agreement between the actual and predicted mean winter $PM_{2.5}$, albeit with a large scatter about the mean 1:1-line. As noted there are some significant experimental uncertainties in the derivation of woodheater numbers near a station, which may contribute to some of the scatter, but equally at some level such a simple, two-parameter approach would be unlikely to capture all intrinsic environmental variation.

A histogram plot of the residuals (actual-predicted $PM_{2.5}$) for the data in Figure 5 is given in Figure 6. The formal mean residual is -0.5 μg/m^3, with a standard deviation of 3.7 μg/m^3. For completeness, it is stated that a mean residual near zero was derived by choice of parameters for the parabolic-fit and wind correction (discussed above) for 14 BLANkET stations. The histogram shown in Figure 6 was derived for actual-predicted $PM_{2.5}$ from all 35 BLANkET stations for all available years of data.

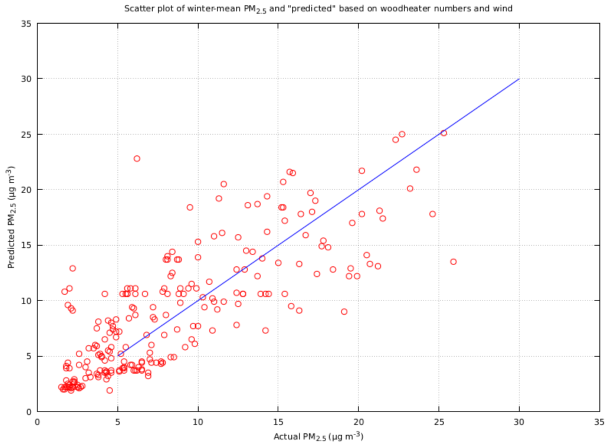

Illustration 5: Scatter plot of measured mean winter $PM_{2.5}$ and two-parameter-predicted winter $PM_{2.5}$ for all years of available data for Tasmania's 35 BLANkET stations. The blue diagonal line represents the 1:1 relationship. See the text for details.

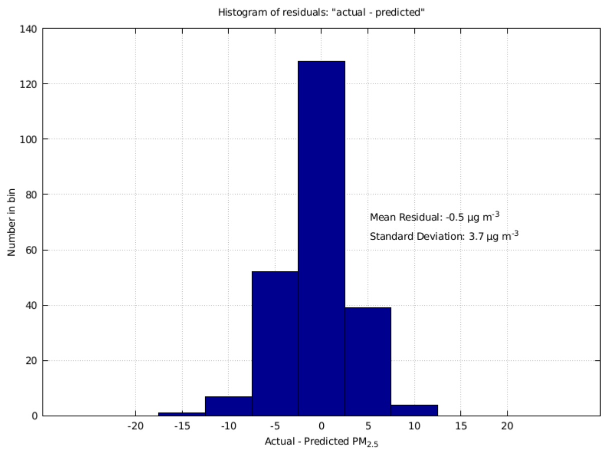

Illustration 6: Histogram of the residuals of actual-predicted mean winter $PM_{2.5}$ for the data shown in Figure 5.

4. Discussion

The analysis presented here indicates that some relationship exists between the number of woodheaters in an area near an air station, and the mean winter $PM_{2.5}$ measured at that station. Some connection between these quantities would indeed be intuitively expected, so in a sense the finding is consistent with this. The work here has tried to more fully investigate the strength of the connection. There is an indication from the analysis that adding a wind-speed dependency provides a more complete description of winter circumstances.

The number of woodheaters and the wind-speed corrections are in a sense a proxy for the underlying physical controllers, of particle emissions to the atmosphere and the rate of local dispersion and mixing. Emission rates of individual woodheaters are likely to vary by woodheater model, time of day, and to also to depend on other factors such as operator technique. The results of the analysis here may be evidence that the ensemble emissions of a group of woodheaters averaged over a winter season may not change greatly from year to year.

Average winter air temperature was deliberately not included in this analysis. There may be advantages in incorporating a temperature term, but it was not considered here for two main reasons: One is that it was thought that providing an extra numerical parameter in the fitting could improve the agreement between measurement and prediction through numerical means, without an underlying physical basis. The other is that the uncertainties on the determination of woodheater numbers around each station is considered to limit the utility of too much detailed analysis at present. Incorporating a temperature term may be appropriate if woodheater estimates become available in future, and if a re-analysis still suggests some relationship between woodheater numbers and winter $PM_{2.5}$.

This work was initiated in response to the need to estimate a state-wide particle population exposure measure. The standard deviation in the residuals of the measured-predicted mean winter $PM_{2.5}$ value, of 3.7 µg/m^3, is relatively large. As it stands the method may only be of use for population exposure estimation for cases where no other means is possible. It is also noted that applying the method may take one problem, that of estimating winter $PM_{2.5}$, and turn it into two problems – estimating woodheater numbers and obtaining knowledge of the local meteorology. For the second point, it is acknowledged that modern numerical weather-databases/reanalyses could provide spatial meteorological data for this application. A detailed comparison of these databases with point observations has not been conducted, but it was noted in other work that wind speeds can be overestimated in some models compared to actual. Resolving these issues would be important if the method outlined here was to be employed.

Spatial knowledge of woodheater use is also critical. In past years in Australia the 3-yearly national census included a home-heating section, but unlike in New Zealand this is no longer the case. There would be a number of reasons why re-instating this would be of benefit in air quality work into the future.

Acknowledgments

The author thanks EPA Tasmania colleagues Elzbieta Chelkowska for assistance with interpreting the 2011 woodheater telephone survey database; Ellis Cox for the spatial data importation and 1 km buffer creation; and all other Air Section members for their contribution and support to the programs that provided the data used in this analysis.

References

Innis, J., di Folco, M., Bell, A., Cox, E., Cunningham, A., Hyde, B., Stanborough, M., and Chelkowska, E., 2017, 'Deriving spatial maps of mean winter-time PM2.5 in Launceston: Steps towards population-exposure estimation', CASANZ17, 'The Critical Atmosphere', Brisbane 2017.

Appendix

The apparent and approximate empirical relationship, reported above, between the number of woodheaters within 1 km of a station and mean winter-time $PM_{2.5}$, viz:

$$\langle PM_{2.5} \rangle \sim N / 20 \qquad (A1)$$

but did not explore how such a relationship may arise. A few comments will be provided in this appendix.

Meyer et al (2008) measured particle emissions from 20 woodheaters in Launceston operating under real-world conditions (Meyer et al., 2008). The average-hourly emission rates (in gram/hour) for the 20 woodheaters measured by Meyer et al. (2008) is shown in the top panel of Figure 7. There are well defined peaks in the late afternoon and late evening, almost certainly related to woodheaters being lit and reloaded respectively. A small subsidiary peak near 8:00 am is likely to reloading or re-lighting of heaters as well. The average hourly-emission rate is near 3 g/hr.

The lower panel shows the hour-averaged $PM_{2.5}$ concentrations measured at Perth station (near Launceston) for the various winter seasons as shown. Very similar time-variation profiles are seen at all Tasmanian stations, although the actual peak concentrations vary. The early afternoon emission peak (top panel) is not reflected in the measured concentrations (lower panel), while the evening emission peak is accompanied by an increase (possibly slightly delayed) in concentrations.

The average emission rate for current Launceston heaters may be slightly different from the 2008 measured value, but the 2008 rates will be used in the following.

For the purposes of this work, the idea is explored that the measured emission profile can be transformed to the measured concentration profile by applying two (hypothetical) functions. The first function is predicated on the assumption that smoke emitted in the early afternoon is more likely to dissipate compared to smoke emitted later in the evening if an inversion layer have formed and strengthened. This will be informally referred to here as the 'lid' function. The emission rates will be multiplied by this function. The second function will try to account for delays between the particle emission and the appearance of smoke at the station – which under calm conditions will be dominated by diffusive processes. This will be called the 'lag' function. Emissions will be convolved with this function.

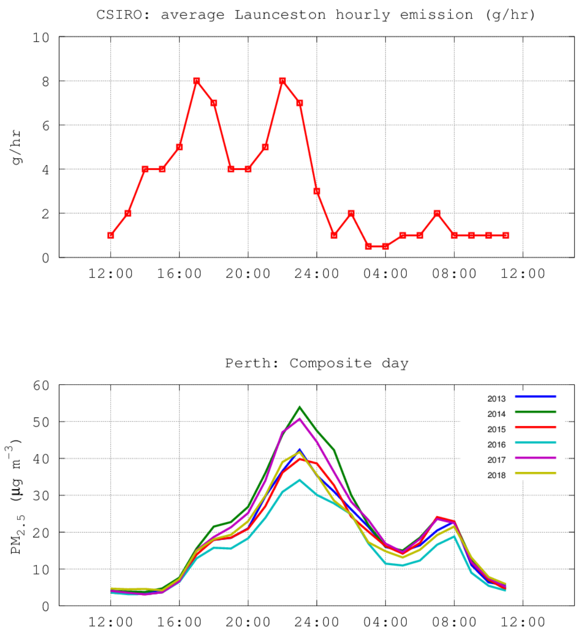

Illustration 7: Top panel: Hourly-emission profile averaged for 20 Launceston woodheaters (Meyer et al., 2008). Lower panel: Hour-averaged $PM_{2.5}$ concentrations for winter-time for Perth (near Launceston).

Note that this is purely a mathematical exploration to see if it is possible to create such functions. Given that the only constraint on these functions is to match the resulting output with the observed hourly concentrations, is it not surprising that it is indeed possible to invent a pair of functions (or even multiple pairs) that give a reasonable result.

A 'lid' and 'lag' function pair is shown in the upper panel (lid) and middle panel (lag) of Figure 8. The lower panel shows the measured Perth hour-averaged winter concentrations, identified by year, and the hypothetical 'concentrations' resulting from the estimated 350 woodheaters in the surrounding 1 km of Perth station assuming:

- each woodheater emits at the average rate measured by Meyer et al. (2008);
- the smoke from these heaters is eventually uniformly dispersed in cylindrical volume of radius 1 km and height 10 m; and
- the lid and lag functions in Figure 8 are applied.

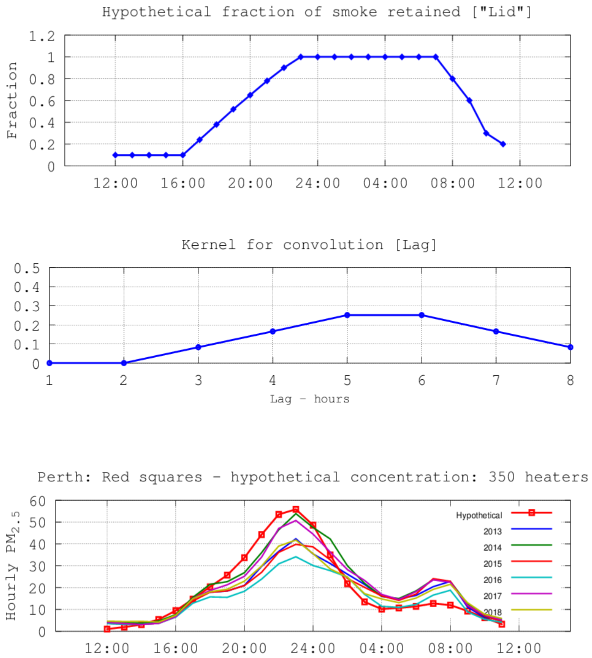

Illustration 8: Top panel: A hypothetical 'lid' function - which may relate to inversion layer strength. Middle panel: A hypothetical 'lag' function, which controls the time between smoke being emitted from a chimney and when it appears at a measurement station. Lower panel: Solid lines, no symbols: Hour-averaged winter $PM_{2.5}$ data from Perth station of the identified winters. Red line with open squares: Resulting smoke concentration based on the emission rates of Meyer et al. (2008), estimated woodheater number near the station, application of the lid and lag functions, and an assumed vertical ceiling of 10 metres.

The uniqueness and physical basis of the 'lid' and 'lag' functions have not been explored in the current work. As noted, given the general lack of constraints in creating the lid and lag functions it is probably not surprising that a final hypothetical concentration profile can be found to match actual concentrations. Also the adoption of a 10-m ceiling is arbitrary, although possibly it has some reasonable physical basis. The derived lag function at face value would suggest some smoke has a residence-time of several hours in the airshed, but it is not clear if this occurs in reality. Overall however the point of this exercise was simply to explore if such an approach could work – whether it provides any physical insight in consequence is an open question.

The approach used here (with a 10 m ceiling) in effect leads to the following simple relation between hourly concentration, C_{hr} (µg/m^3), and emission, E (g/hr), of

$$C_{hr} = N \times E \times 10^6 / 3.14 \times 10^7 \qquad \text{(A2)}$$

where N is the number of heaters within a 1 km radius, and with the assumption that the emissions in any given hour relate to the concentration in that hour. (This is applying a steady-state approach to a dynamic process, so it is clearly an approximation.)

The mean hourly emission, averaged over a day, is near 3 g/hr, as noted above. The overall effect of the lid and lag functions is to reduce the emission to an effective-emission rate near 1.7 g/hr. Substituting this for E in equation (A2) yields

$$C_{hr} \sim N / 18. \qquad \text{(A3)}$$

As noted there are many assumptions and approximations that have been used here, but the interesting similarity with equation A1 is noted. Much more work needs to be conducted however before it could be concluded that there is some underlying physical justification for this relationship.

For completeness, it is of interest to apply the 'lid-lag' approach to a further hypothetical consideration, where the late-evening peak in woodheater emissions is not present. That is, a scenario where woodheater operators do not reload their heaters during the late evening (when the inversion is likely to be present) but rely instead, say, on improved insulation keeping the house warm at night following the late afternoon woodheater-fuellling.

Figure 9 shows in the top panel the CSIRO measured averaged-emissions (red squares) and a hypothetical, modified emission profile (blue diamonds) where the evening peak is not present. The lower panel shows the inferred $PM_{2.5}$ concentrations after applying the 'lid' and 'lag' functions, as was done for Figure 8, for each emission scenario. Not unexpectedly, the day-averaged $PM_{2.5}$ concentration is approximately halved when the evening emissions are not present. The peak-hourly $PM_{2.5}$ is also greatly reduced. It is explicitly stated again it is not yet clear if there is any physical basis to this 'lid and lag' arithmetic approach, but as it stands, it is suggestive that there may be improved air quality outcomes if the level of late evening woodheater emissions could be significantly reduced.

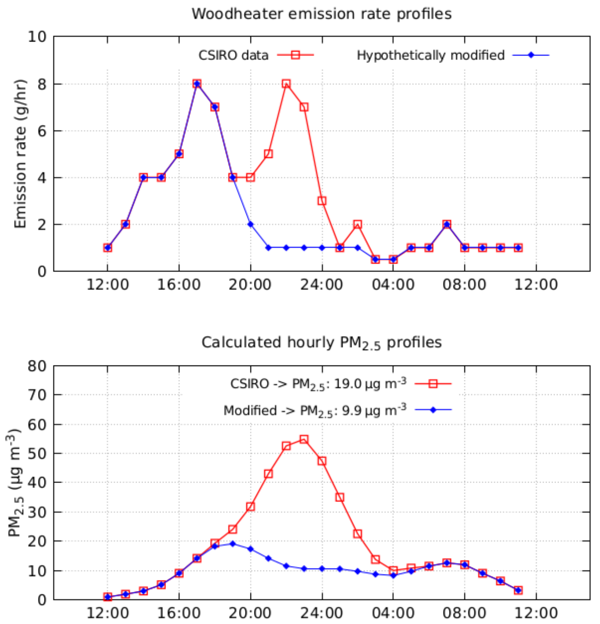

Illustration 9: Top panel: CSIRO measured average-woodheater emissions (red squares) and a scenario where the late evening emissions are not present (blue diamonds). Lower panel: Resulting (hypothetical) $PM_{2.5}$ concentrations after applying the 'lid' and 'lag' functions to the woodheater emission rates. For the case where the late evenng emission peak is not present, the day-averaged $PM_{2.5}$ is approximately halved. The peak hourly $PM_{2.5}$ is also significantly reduced.

Reference

Meyer, C.P,. Luhar, A., Gillet, R., Keywood, M., 2008, 'Measurement of real-world PM_{10} emission factors and emission profiles from woodheaters by *in situ* source monitoring and atmospheric verification methods', CSIRO publication.